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ASD TDR-63-581

FINAL REPORT ON MACHINING OF REFRACTORY MATERIALS

TECHNICAL DOCUMENTARY REPORT NR. ASD-TDR-581
July 1963

Advanced Fabrication Techniques Branch
Manufacturing Technology Division
Air Force Materials Laboratory
Air Force Systems Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

ASD Project Nr. 7-532a

(Prepared under Contract AF 33(600)-42349 by
Metcut Research Associates Inc., Cincinnati Ohio
N. Zlatin M. Field, and J. V. Gould)

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FOREWORD

This Final Technical Report covers the work performed under Contract AF 33(600)-42349 from 7 November 1960 to 31 May 1963. It is published for technical information only and does not necessarily represent the recommendations, conclusions, or approval of the Air Force.

This contract with Metcut Research Associates Inc., Cincinnati, Ohio, was initiated under ASD Manufacturing Technology Division Project Nr. 7-532a, "Machining of Refractory Materials." It is being administered under the direction of Mr. Robert T. Jameson of the Advanced Fabrication Techniques Branch (ASRCT-40), Manufacturing Technology Division, Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio.

Mr. Norman Zlatin, Director of Machinability Research at Metcut, is the engineer in charge of this program. Others who have cooperated in the investigation reported herein and preparation of the report were Mr. John V. Gould, Project Engineer, and Dr. Michael Field, Research Director. This project has been given the Metcut Research Internal No. 470-3300.

The primary objective of the Air Force Manufacturing Methods Program is to increase producibility, and improve the quality and efficiency of fabrication of aircraft, missiles, and components thereof. This report is being disseminated in order that methods and/or equipment developed may be used throughout industry, thereby reducing costs and giving "MORE AIR FORCE PER DOLLAR."

Your comments are solicited on the potential utilization of the information contained herein as applied to your present or future production programs. Suggestions concerning additional development required on this or other subjects will be appreciated.

ABSTRACT
Final Technical Documentary Report

ASD TR 7-532a
May 1963

MACHINING OF REFRACTORY MATERIALS

Norman Zlatin
Michael Field
William P. Koster
John V. Gould

Metcut Research Associates Inc.

In this program, the machining characteristics were determined for unalloyed tungsten, molybdenum, columbium and tantalum alloys, Rene 41, B-120VCA titanium, D6AC steel quenched and tempered to 52-58 R_c, Refrasil, Pyroceram, zirconium oxide and aluminum oxide coatings. The selection of this group, representing the most difficult to machine materials presently being fabricated into aerospace components, is the result of a field survey.

Most of the machining operations on these materials can be performed with reasonable tool life, provided that specific machining conditions are employed. This report presents the recommendations for machining these materials. It should be noted that even small deviations in cutting speed, feed, cutting fluid, tool material and tool geometry can result in significant reductions in tool life.

Tests were also conducted on 1) high speed edge milling of high temperature sheet materials and 2) the Tornetic system of drilling and tapping. Successful edge trimming of the high temperature sheet was accomplished in the cutting speed range of 500 to 2000 feet/minute. The Tornetic system has its principal advantage over standard equipment in that it provides a continuous variable cutting speed and feed which, on some materials, makes possible a more efficient cutting condition. In addition, the Tornetic system has the capability of limiting the available torque on the tool, and thereby eliminates tool breakage.

PUBLICATION REVIEW

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TABLE OF CONTENTS

I. INTRODUCTION

This report is a summary of all of the machinability tests performed in Phase II of the subject contract.

The refractory alloys and high strength thermal resistant alloys tested in this program include some of the most difficult to machine materials encountered to date. The use of significant quantities of most of these alloys for structural purposes was initially unknown five years ago. Today, however, advances in aerospace flight systems are bringing into production many components made from these materials.

Recognizing problems to be encountered in machining these materials, the Advanced Fabrication Techniques Branch, Manufacturing Technology Division, Air Force Materials Laboratory, Aeronautical Systems Division, Air Force Systems Command, has sponsored a program to develop appropriate machining data. The materials studied in connection with this program were as follows:

- Unalloyed tungsten, pressed and sintered, forged and resintered and arc cast
- D-31 columbium alloy
- TZM and Mo-0.5 Ti molybdenum alloy
- 90Ta-10W tantalum alloy
- B-120VCA titanium alloy
- Rene 41 alloy
- D6AC steel quenched and tempered to 54-58 R_c
- Silica fiber reinforced phenolic resin (Refrasil)
- High temperature glass (Pyroceram)
- Aluminum oxide and zirconium oxide coatings

In addition, a preliminary evaluation of two relatively new machining techniques has been performed. A high speed edge milling program was carried out in edge trimming high temperature sheet materials, 1/16" to 1/4" thick, at cutting speeds of 500 to 2500 feet/minute. An evaluation of the Tornetic system in drilling and tapping aerospace alloys was also made.

The results of this program are summarized in this report.

II. EQUIPMENT AND TESTING PROCEDURES USED

Turning

All of the turning tests described in this report were conducted on an American Pacemaker 16" x 30" lathe equipped with a variable speed drive, illustrated in Figure 1, page 6. The spindle rpm could be varied to maintain the required cutting speed for any workpiece diameter. Carbide, high speed steel, oxide and cast alloy tools were used in the turning tests. The turning test bars were 3" to 4" in diameter by 18" long. A skin cut of .100" depth was taken on each test bar prior to making a turning test, to remove any surface effects. Both throwaway insert and brazed carbide tools were used.

The nomenclature for the single point lathe tools is shown in Appendix A, page 331.

Face Milling

The face milling tests were performed on a Cincinnati No. 3 Horizontal Dial Type Milling Machine. This machine is shown in Figure 2, page 7. Single and multiple tooth carbide, high speed steel and cast alloy cutters were also used in face milling. The setups used are shown in Figure 3, page 8.

The milling test bars were clamped in position on the milling machine using a specially designed fixture to insure maximum rigidity. All test bars were 2" thick by 4" wide by 10" long. In most tests the 2" side was milled; thus, the width of cut was 2". A clean-up machining cut of 0.100" depth was made on all sides to remove any surface effects on the test bar.

Tool geometry, tool material, cutting speed and feed were evaluated using a 4" diameter single tooth inserted cutter. A 4" diameter 4 tooth face milling cutter with inserted carbide tipped blades was used for multiple tooth milling tests. The nomenclature for a typical face milling cutter is shown in Appendix B, page 332.

Slotting

The slotting tests were made on the Cincinnati No. 3 Horizontal Dial Type Milling Machine. A 2" diameter arbor was used to hold the cutter. Maximum rigidity in the setup was obtained by mounting the cutter as close as possible to the spindle nose of the machine and by using two closely spaced arbor supports. The test bars were rigidly clamped in a fixture which was bolted to the table of the machine.

A single tooth carbide tipped slotting cutter was used in these tests. One inch wide slots were milled through the full length of the test bars. Depth of cut in these tests varied from 1/8" to 1/4". Tool life is expressed in inches of work

Slotting (continued)

travel for a specified wearland on the peripheral cutting edge. The slotting setup is illustrated in Figure 4, page 9.

The cutter used for slotting tests was a 6" diameter, 1" wide, 6 tooth cutter with inserted carbide tipped serrated blades. This same cutter was used for single tooth tests by employing dummy blades in five of the six tooth spaces.

End Milling

The end milling tests were made on the Cincinnati No. 2 Dial Type Vertical Milling Machine shown in Figure 5, page 10. The test bar was clamped in an 8" heavy duty vise attached to the milling machine table. Straight shank end mills were used and held in the machine with an adapter. In addition to the standard integral cutting fluid system, the machine was equipped with a spray mist applicator system and a hollow draw bar for applying cutting fluids through hollow shank cutters, in order to evaluate cutting fluid application methods.

The test bars were 3" x 3" x 10" long. All heat treated bars were first face milled to a depth of 0.100" to remove any surface effects on the bars.

Full width cuts 1/4" to 3/4" deep were made in 10" long test bars, as shown in Figure 6, page 11. Tool life is expressed in inches work travel to obtain the specified wearland on the tool.

Both high speed steel and carbide end milling cutters were used. The high speed steel cutters used were 3/4" and 1/2" diameter, 4 flute right hand spiral, right hand cut. The carbide tipped end mills used were specially designed with a shank diameter equal to the cutter diameter of 1-1/4", a cutter length of 3-1/4" and a flute length of 1". This design reduced cutter deflection to a minimum. The nomenclature for end mills is illustrated in Appendix C, page 333.

Drilling

The drilling tests were performed on a 25" Fosdick upright drill press and a Cincinnati 16" sliding head box column drilling machine equipped with an infinitely variable speed drive to produce any desired spindle speed in the speed range of 220 to 4500 rpm. An additional variable speed unit was used to drive the feed mechanism, making available feeds ranging from 0.0001 in./rev. to 0.015 in. per rev. This equipment is illustrated in Figure 7, page 12. The drilling test samples were 1/2" thick plates cut from the 2" x 4" milling bar stock. A face milling cut of 0.060" was made on both faces of each plate to remove any surface effects and provide a smooth surface for drilling.

Most of the drilling tests were performed using 1/4" diameter high speed steel drills. Some tests were performed with smaller size drills. Drills made from several types of high speed steels were used.

Drilling (continued)

The drill nomenclature for standard point and crankshaft point grind is illustrated in Appendix D and E, pages 334 and 335.

Tapping

The 25" Fosdick upright drill press shown in Figure 7, page 12, was used for the tapping tests. The tapping test samples were 1/2" thick plates. Tap drill and reamer sizes were used to obtain 60%, 70% and 75% threads. The tapping tests were run with 5/16-24 NF and 1/4-28 NF taps made from several high speed steels. Tap nomenclature is indicated by Appendix F, page 336.

Grinding

A Norton 8" x 24" Hydraulic Surface Grinder equipped with a 2 H.P. variable speed spindle drive was used for the grinding tests. This grinder is shown in Figure 8, page 13, and the test setup is shown in Figure 9, page 14. A fixture was used to hold the test specimens, which were 1" square and 5" long. This fixture was slotted at both ends and in the center, so that specimen thickness measurements could be made without removing the specimen or fixture from the machine. The effects of grinding conditions on grinding ratio (G) were evaluated.

The grinding ratio (G) is a measure of grinding wheel life, analogous to tool life in other machining operations, and is defined as:

$$G = \frac{\text{Volume Metal Removed}}{\text{Volume Wheel Removed}}$$

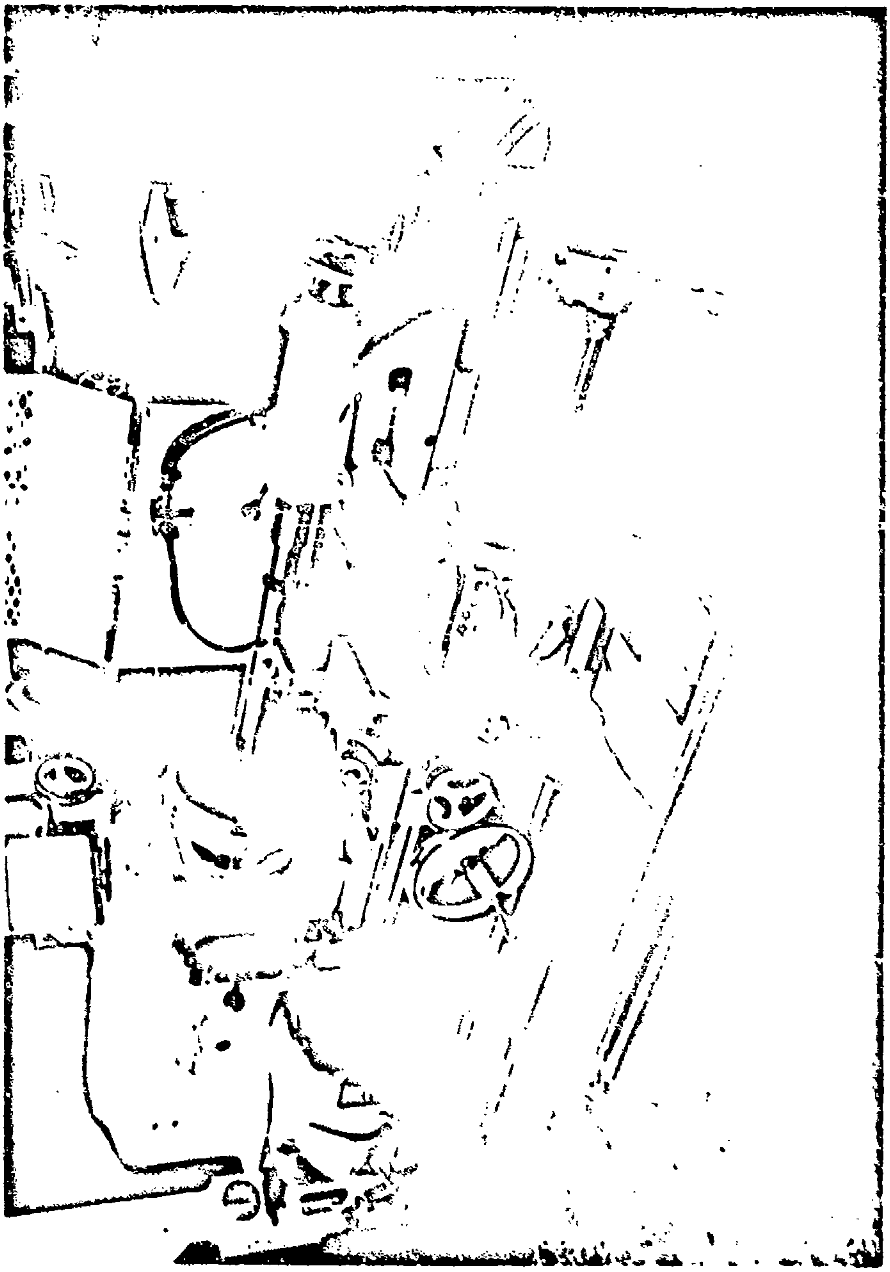
A wheel size of 10" x 1" x 3" was used for all tests.

The following procedure was used for grinding tests. Before the grinding tests were started, a 0.030" deep by 1/2" wide step was dressed in the grinding wheel, see Figure 9, page 14. This step was used as a reference in measuring wheel wear. A 0.0001" dial indicator mounted on a fixture attached to the wheel housing was brought in contact with this step and the indicator was set to read zero. The indicator was then moved to the upper step or grinding surface of the wheel and the initial reading was taken. Indicator readings were taken after every 0.025 to 0.050" metal removal to a total metal removal of about .100". The difference between the initial indicator reading and successive readings was the amount of wheel removed from the wheel radius. The initial outside diameter of the wheel was accurately measured before each test with a vernier caliper. The volume of wheel removed was calculated from initial and final wheel diameter measurements.

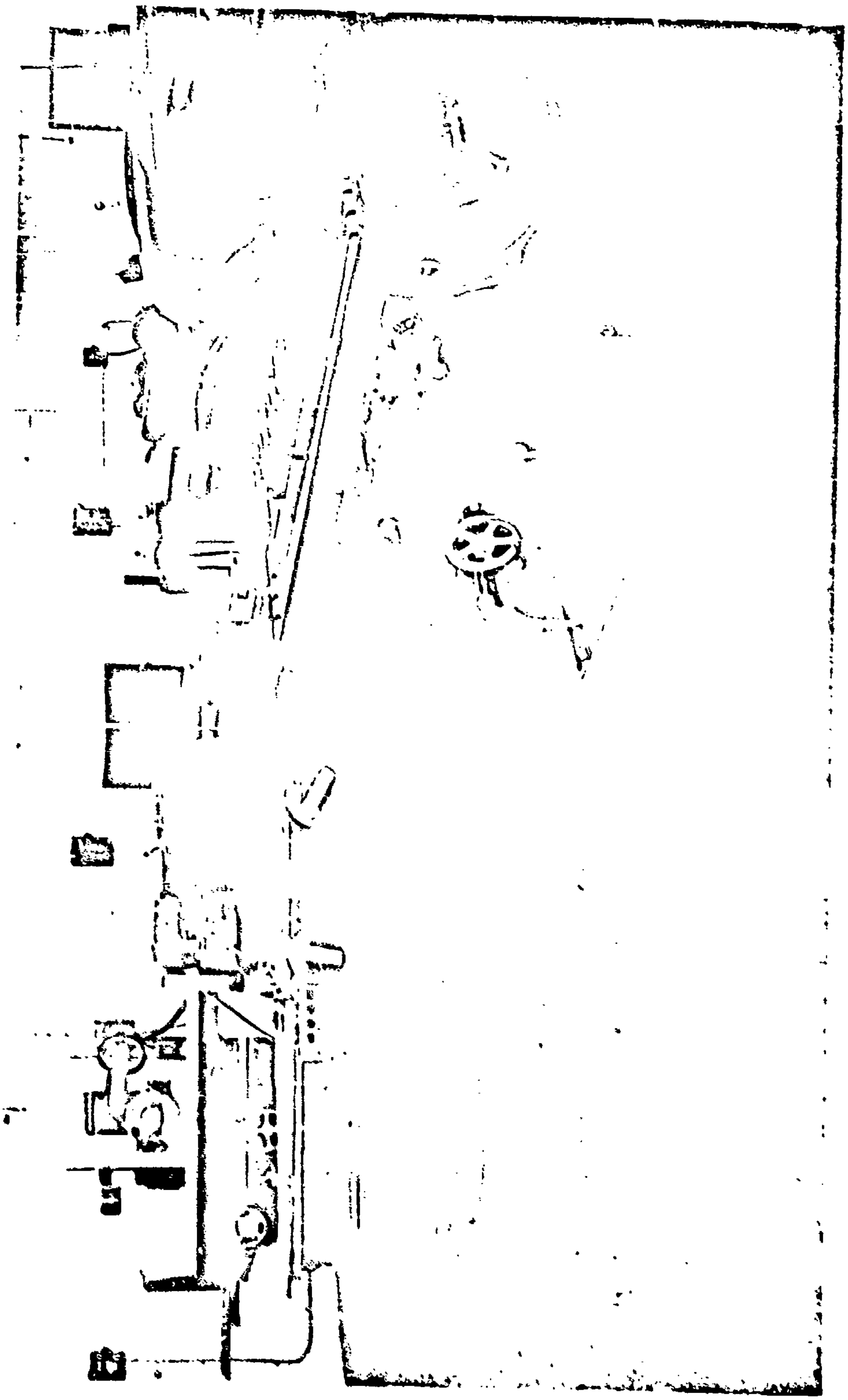
Grinding ratios were calculated at each 0.025" stock removed, and an average taken to arrive at a final G ratio value. All specimens were examined for surface cracking visually and by the "Dy-Chek" method.

Cutting Tool Nomenclature

High speed steel, cast alloy and carbide cutting tools were used for this program. In general, the commercial designation for these materials is used throughout this report. An identification of these cutting tool materials is presented in Appendix G, page 337. A hardness conversion chart is shown in Appendix H, page 338.



16" x 30" American Pacemaker Lathe equipped with a 30 H. P. infinitely variable speed drive to provide exact cutting speed control for turning tests.

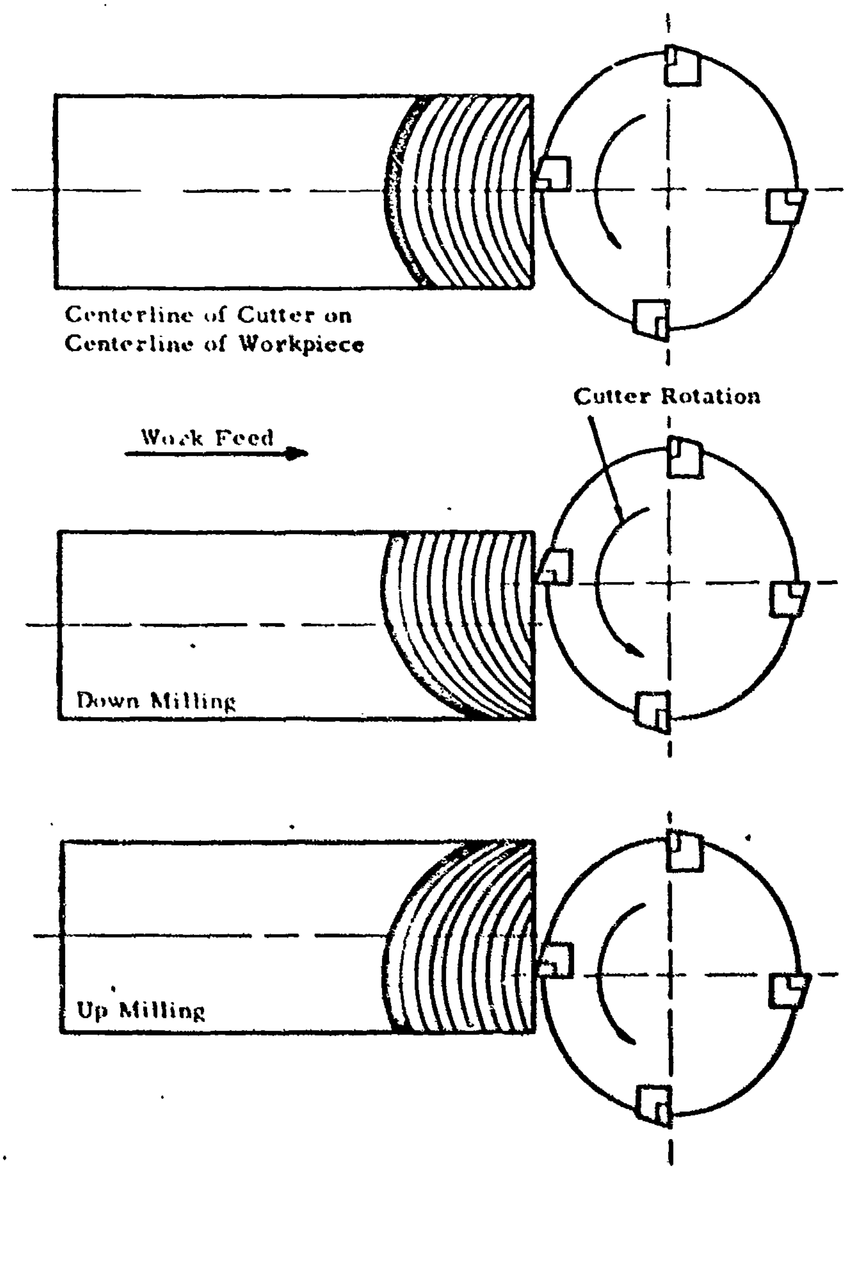


Face milling tests were made on a Cincinnati No. 3 Horizontal High Speed Dial Type Milling Machine. Shown in the background is a Cincinnati 12" x 36" Hydraulic Universal Grinder and a Gallmeyer & Livingston No. 55 Hydraulic Feed Surface Grinder.

See Text, page 2

Figure 2

Face Milling Setups
Illustrating Up and Down Milling



See Text, page 2

Figure 3

Slotting Nomenclature and Setups
Illustrating Conventional and Climb Milling

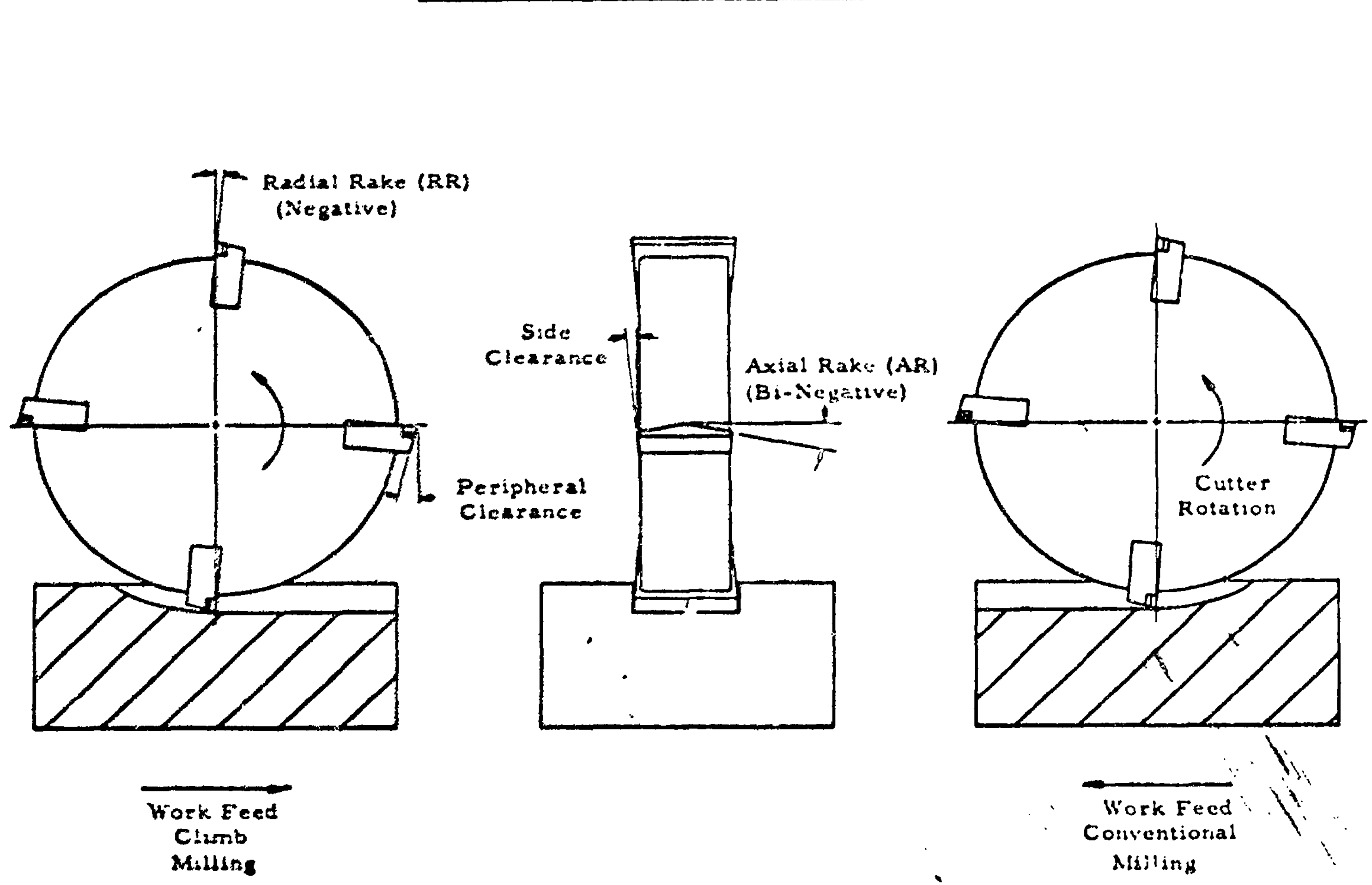
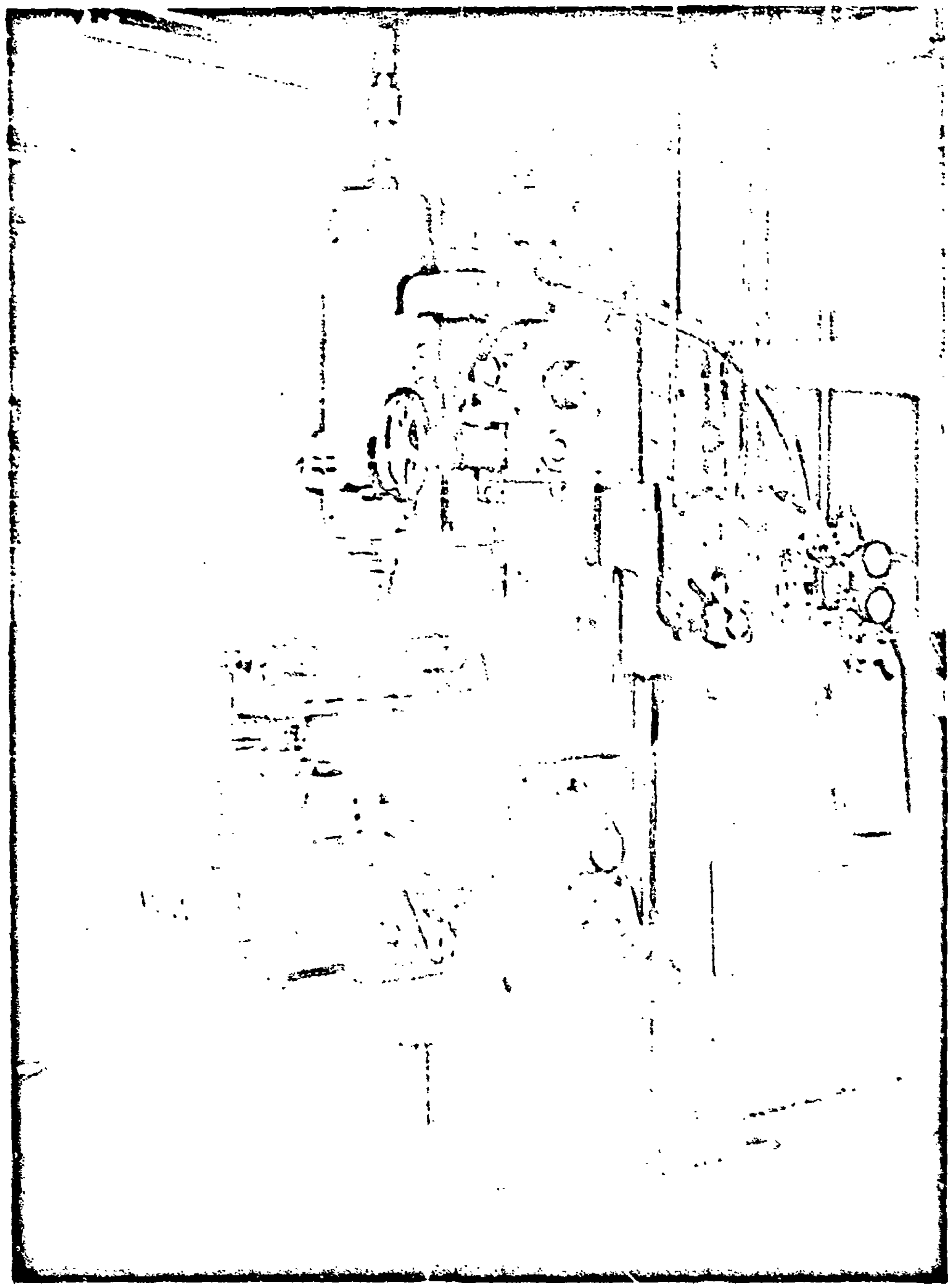
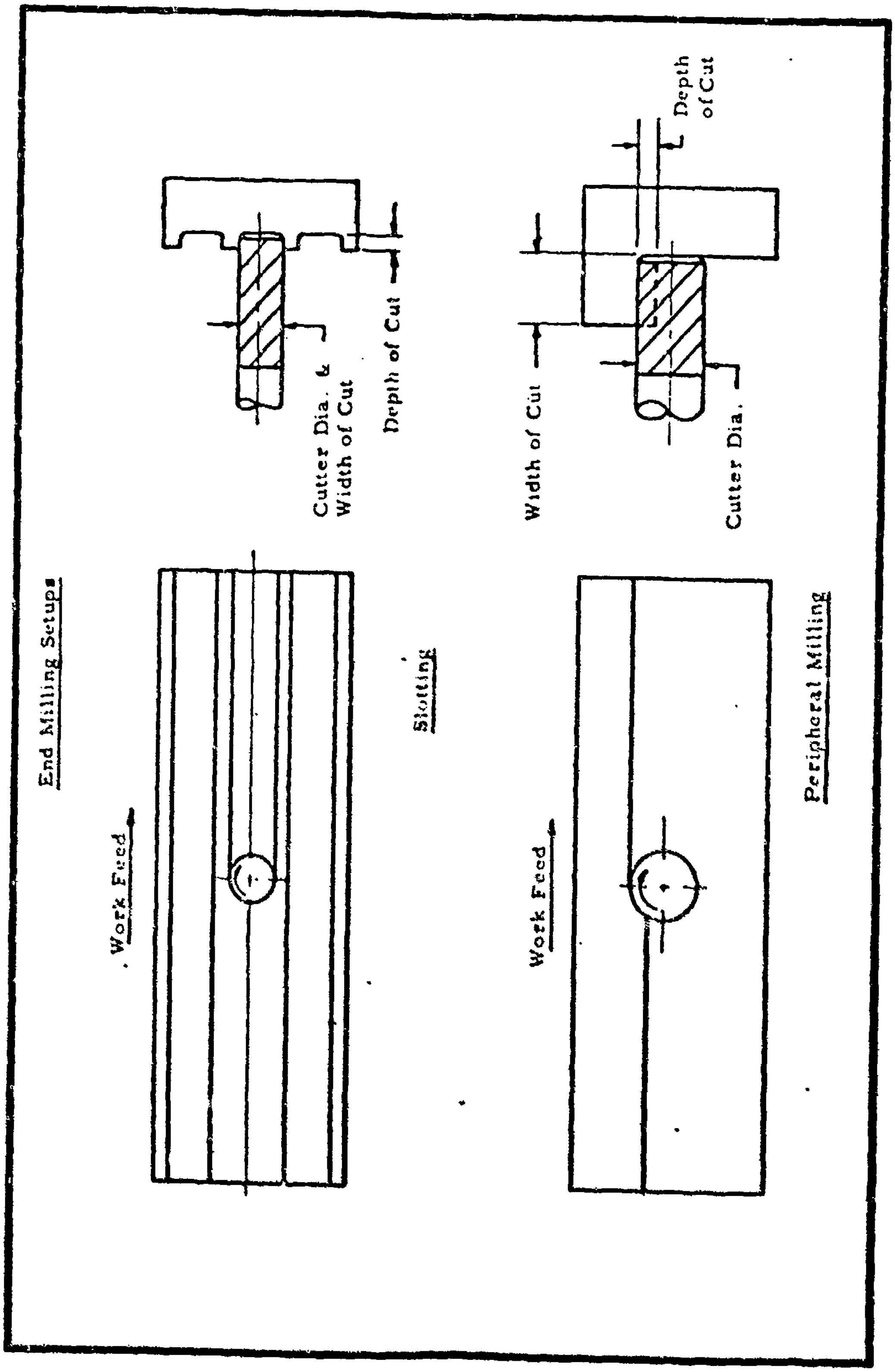


Figure 4

See Text, page 3

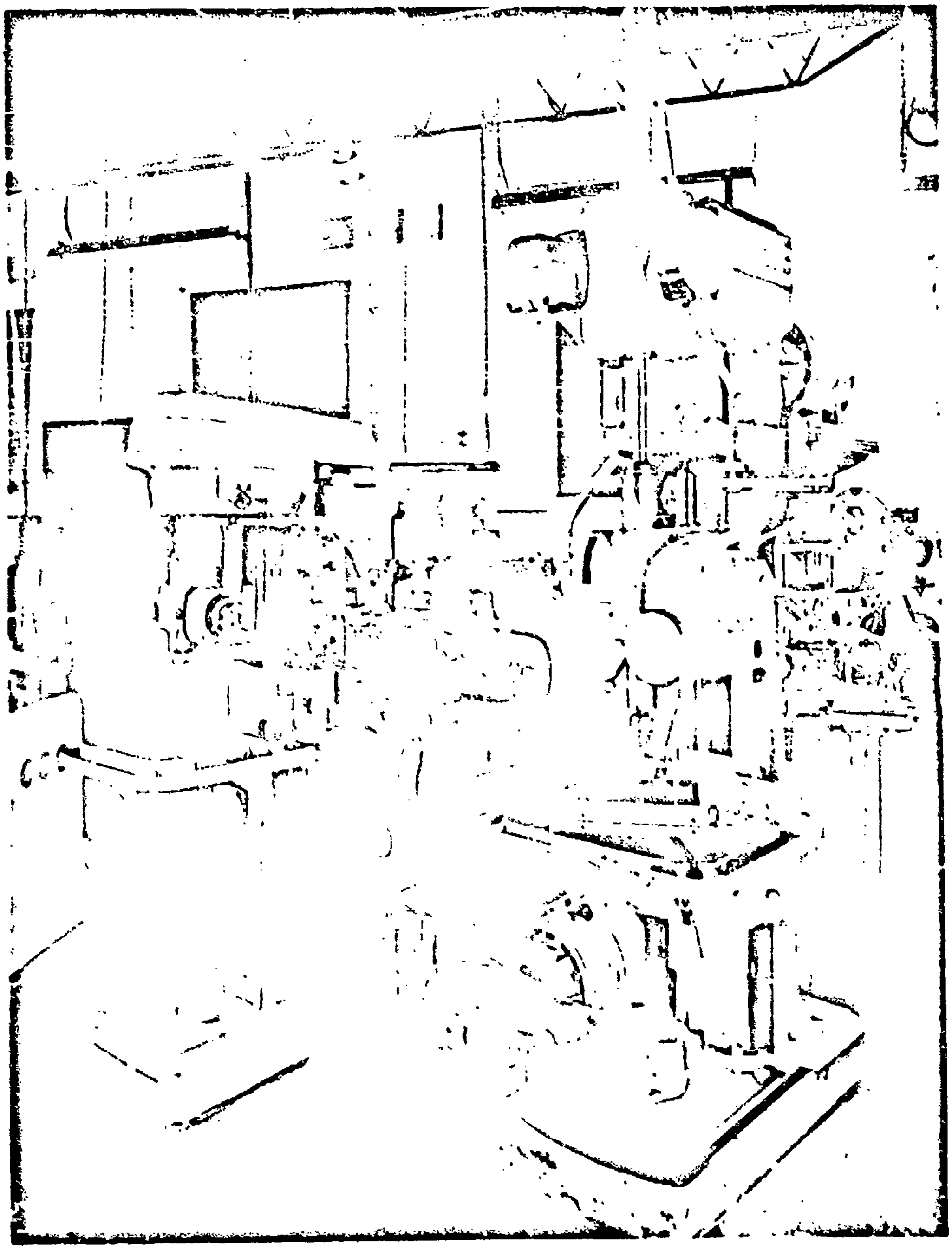


End milling tests were performed on a Cincinnati No. 2 Vertical Dial Type Milling Machine. A spray mist cutting fluid applicator is shown on the machine. A rotary seal is shown attached to the top of a hollow draw bar for applying spray mist or cutting fluid through a hole along the axis of the rotating cutter.

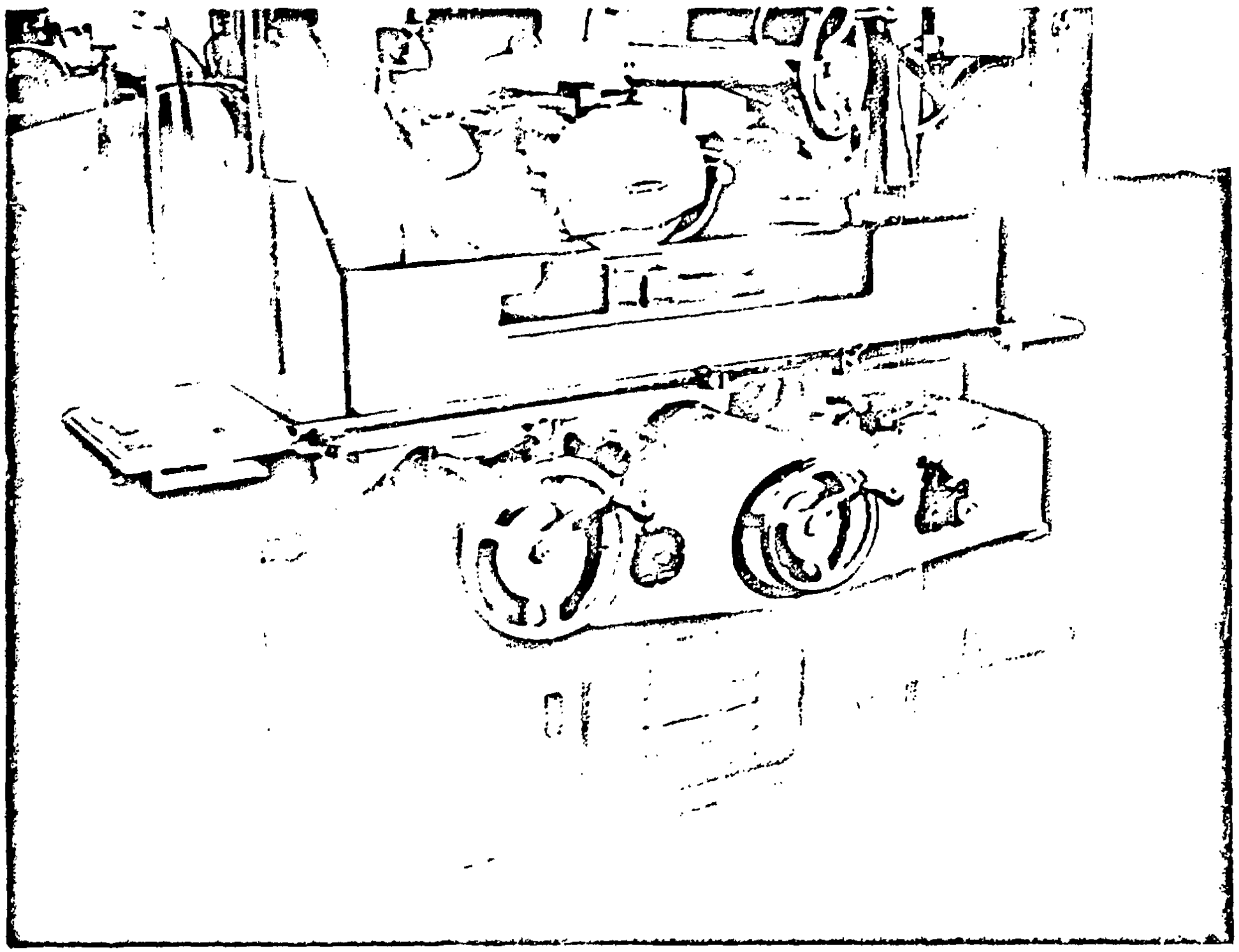


See Text, page 3

Figure 6



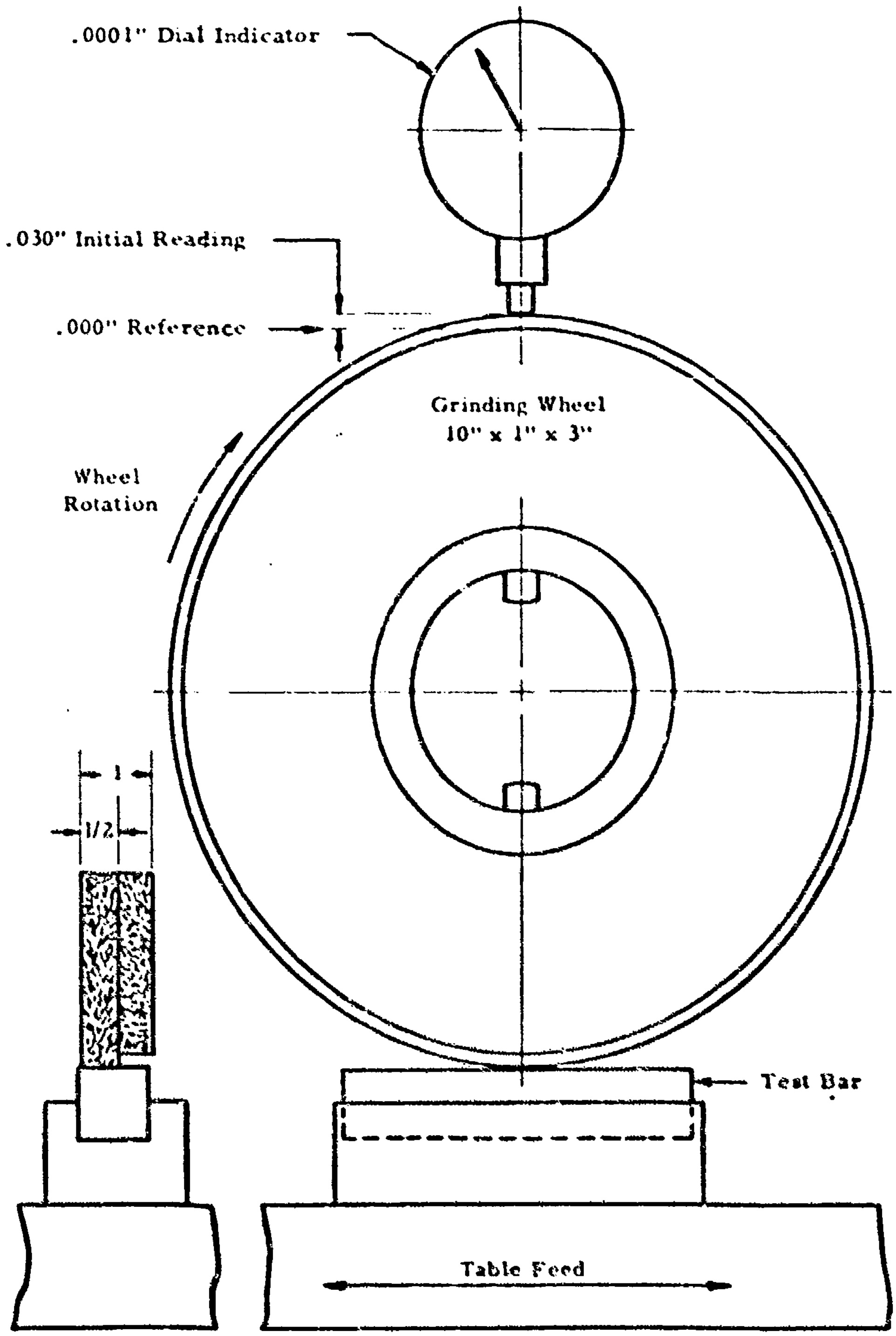
Drilling tests were performed on a Fosdick 25" Upright Box Column Drill Press (right) and a Cincinnati 16" Box Column Drilling Machine. Both machines are equipped with infinitely variable feed drive units to provide feeds from .0001 to .025 inches/rev.



Surface grinding tests were performed on a Norton 8" x 24" Hydraulic Surface Grinder equipped with an infinitely variable speed drive. Grinding speeds ranging from 1000 to 7500 surface feet per minute can be obtained.

Figure 8

See Text, page 4



GRINDING TEST SETUP

III. MACHINING UNALLOYED TUNGSTEN

The propulsion systems of current aerospace weapons require structural materials capable of operating at very high temperatures. These temperatures often exceed the melting points of nickel- and cobalt-base super alloys. Refractory alloys, therefore, must be considered for such applications.

Unalloyed tungsten, which possesses useful structural strength even above 5000°F, has an outstanding potential for use in this area. Rocket nozzles and deflector vanes have been most frequent applications of tungsten.

From a practical standpoint, however, there are some very real obstacles to be overcome in working with tungsten. Machining operations are inherently difficult. Lack of ductility at room temperature is another limitation. This characteristic complicates fabrication and also poses sizable problems in the design of tungsten structures.

The unalloyed tungsten investigated in this report can be classified by these categories:

- Pressed and sintered tungsten
- Forged and resintered tungsten
- Arc cast tungsten

Materials having theoretical densities of 85 to 96% were machined in the pressed and sintered form. The forged and resintered tungsten machined in this program had a theoretical density of 96%, while the arc cast tungsten investigated was 99% dense.

Microstructures of the tungsten discussed in this report are shown in Figures 10, 11 and 12, pages 27, 28 and 29. The structures of the pressed and sintered materials, including the sintered and subsequently forged grade, exhibit small grain boundary voids among the grains of unalloyed tungsten. The arc cast material, which has a much larger grain size than the other grades, is essentially free of voids in the microstructure.

The chemical analysis of these tungstens are shown in Table 1. No heat treatment was performed on any of these materials.

Table 1
Chemical Analysis of Unalloyed Tungsten

	Nominal Analysis, Percent							
	O	N	C	Mo	Mn	Si	Co	W
Pressed and Sintered	.005	.002	.010	.02	.001	.01	.01	Bal
Forged and Resintered	.005	.001	.010	.02	.001	.01	.01	Bal
Arc Cast	.002	.001	.004	.50	--	--	--	Bal

Recommendations for Machining Unalloyed Tungsten

Tungsten is available in several forms. Initial production involves consolidation by pressing and sintering tungsten powder. Variable densities may be achieved by this process. High density tungsten, greater than 90%, is favored over the lower density material for aerospace applications. From a production standpoint, however, the higher density material presents more problems because of its poorer machinability.

Tungsten is very much less ductile at room temperature than the other refractory alloys, although the ductility increases substantially when heated to about 600°F. Due to the brittleness of tungsten at room temperature, chipping, flaking and breakout tend to occur on the edges of machined surfaces. Tool life, production rate and surface finish are poor with rotating cutting tools. Even in grinding, there is a tendency to produce cracking of the workpiece.

Details of the machining variables of unalloyed tungsten are discussed in the following sections. Recommendations for machining are summarized in Table 2, pages 30 and 31.

Turning Pressed and Sintered Tungsten, 93% Density

Figures 13 through 17, pages 32 through 34, show the tool life curves obtained when turning unalloyed tungsten of 93% theoretical density.

The effect of cutting speed is shown in Figure 13, page 32, when turning this material with three different carbide grades. Standard negative rake throwaway tool geometry (BR -5°, SR -5°) was employed in all the tests. Using a feed of .009 in./rev. and the hard non-ferrous K-11 (C-4) grade, best tool life of nine minutes was obtained at a cutting speed of 200 feet/minute. Tool life decreased to three minutes when the cutting speed was increased to 300 feet/minute and also decreased when the cutting speed was decreased to 100 feet/minute.

At a cutting speed of 200 feet/minute, a C-2 non-ferrous grade 883 carbide provided a tool life of only two minutes, while a C-8 steel cutting grade provided less than one minute tool life.

Figure 14, page 32, shows the effect of feed when turning tungsten at a cutting speed of 200 feet/minute using the standard negative rake tool geometry. This chart shows that maximum metal removal rates were obtained at feeds of .012 to .015 in./rev. Approximately 12 cubic inches of metal was removed when this feed range was used. When the feed was reduced to .005 in./rev., less than four cubic inches of metal were removed. It should be noted, however, that there is a greater tendency for chipping with the heavier feeds.

Tool life data obtained in turning 93% dense unalloyed tungsten when the back rake and side rake angles were varied over a wide range is shown in Figure 15, page 33. Best tool life was obtained with a 0° side rake angle and a 15° negative back rake angle. At a cutting speed of 200 feet/minute, this geometry provided a tool life of 16 minutes.

Turning Pressed and Sintered Tungsten, 93% Density (continued)

A tool life curve using this geometry is shown in Figure 16, page 33, over a cutting speed range of 100 to 300 feet/minute. Also shown is a tool life curve obtained with the standard negative rake throwaway tool geometry (BR -5°, SR -5°). These two curves show the increased tool life obtained with a side rake of 0° and a back rake of 15° negative on the tool which provided a tool life of only 19 minutes at a cutting speed of 100 feet/minute.

Figure 17, page 34, shows the tool life obtained when turning unalloyed tungsten of 93% theoretical density with cast alloy and Type T-15 high speed steel tools. These tool materials were ineffective in turning this material. A tool life of two minutes was obtained with T-15 high speed steel at 25 feet/minute. At this same cutting speed, Crobalt No. 2 cast alloy provided only one minute of tool life, while Stellite 98 M2 and Tantung G provided less than one minute.

Face Milling Pressed and Sintered Tungsten, 85% Density

The data obtained in face milling pressed and sintered unalloyed tungsten of 85% theoretical density is presented in Figures 18 through 22, pages 34 through 37.

Figure 18, page 34, shows the effect of carbide grade and one cast alloy tool material in face milling the tungsten material. The maximum tool life, 24 inches of work travel per tooth, was the same for both the C-3 and C-4 grades of carbide at a cutting speed of 100 feet/minute and a feed of .012 in./tooth. A C-2 carbide grade was slightly inferior, while the cast alloy tool material was completely ineffective.

In face milling tungsten of 85% theoretical density, the best tool life was obtained with a carbide cutter having a 0° axial rake and a 0° radial rake, see Figure 19, page 35. A tool life of 43 inches of work travel per tooth was obtained at a cutting speed of 230 feet/minute and a feed of .012 in./tooth using this cutter geometry. Severe chipping of the workpiece occurred when other tool geometries were used. Figure 20, page 36, shows some examples of workpiece chipping, flaking and breakout in milling and drilling unalloyed tungsten.

The effect of cutting speed and feed is shown in Figure 21, page 37. When face milling at a cutting speed of 360 feet/minute, tool life decreased as the feed per tooth was increased. At a lower cutting speed of 100 feet/minute, tool life increased when the feed was increased. However, severe workpiece chipping occurred at a feed of .020 in./tooth.

The pressed and sintered tungsten bars, 85% density, used in this series of face milling tests were produced by pressing the tungsten powder into a single bar 2" x 4" x 12". This bar was cut prior to sintering into three shorter bars. In performing milling tests on the bars, it was found that each bar had different machining characteristics. A metallurgical examination showed that each bar has a different hardness and grain size.

Face Milling Pressed and Sintered Tungsten, 85% Density (continued)

The tool life curves for the tungsten, 85% density, at two different hardnesses is shown in Figure 22, page 37. The tungsten bar which showed the higher hardness of 90 R_B gave considerably better tool life than the bar of 84 R_B hardness. A tool life of 42 inches fo work travel per tooth at a cutting speed of 230 feet/minute was obtained from the bar of 90 R_B hardness, while the tool life for the bar of 84 R_B hardness was 24 inches of work travel per tooth at a cutting speed of 100 feet/minute. The grain size of the 90 R_B tungsten bar was finer than that observed in the tungsten bar of 84 R_B hardness.

In face milling tungsten of 85% theoretical density, a considerably better tool life was obtained with a highly chlorinated cutting oil as compared with a soluble oil cutting fluid, Figure 23, page 38. At a cutting speed of 100 feet/minute, a tool life of 72 inches of work travel per tooth was obtained with high chlorinated oil, as compared to a tool life of 24 inches of work travel per tooth with soluble oil.

Face Milling Pressed and Sintered Tungsten, 93% Density

The data obtained in face milling pressed and sintered unalloyed tungsten of 93% theoretical density is presented in Figures 24 through 26, pages 38 and 39.

The effect of carbide grade in face milling this material is shown in Figure 24, page 38. A tool life of 20 inches of work travel per tooth was obtained for grade 999 (C-4) and grade K-8 (C-3) carbides at a cutting speed of 97 feet/min. and a feed of .010 in./tooth. Grade 883 and grade K-11 carbides provided slightly less tool life. The relatively small difference in tool life indicates it might be preferable to use the more shock resistant non-ferrous C-2 grade rather than the C-3 and C-4 finishing grades. A steel cutting grade 370 (C-6) provided less than five inches of work travel per tooth.

The effect of cutting speed is shown in Figure 25, page 39, for two grades of carbide and three high speed steel and cast alloy tools. Maximum tool life for two carbide grades was obtained at a cutting speed of 78 feet/minute. With a grade 999 (C-4) carbide, a tool life of 27 inches of work travel per tooth was obtained at this cutting speed using a feed of .010 in./tooth. A grade 883 (C-2) carbide provided 24 inches work travel per tooth under these cutting conditions. Less than five inches was obtained with Braecut, T-15 and T-1 high speed steel at a cutting speed of 20 feet/minute. When using the cast alloys — Crobalt No. 2, Stellite 98 M2 and Tantung G — less than one inch work travel per tooth could be obtained.

The effect of workpiece temperature when face milling unalloyed pressed and sintered tungsten of 93% theoretical density is shown in Figure 26, page 39. For these tests the workpiece was heated with an oxy-acetylene torch. A chromel-alumel thermocouple was attached to the workpiece very near the surface to be

cut. The workpiece temperature was recorded on a conventional temperature recording instrument. The temperature drop was less than 50°F when making the cut.

Tool life increased to a maximum of 11 inches of work travel per tooth when the workpiece temperature was increased to 800°F. At temperatures above 800°F, tool life dropped off. In addition, a very rough surface finish was obtained at workpiece temperatures of 800°F and higher. It is significant to note that considerably better tool life, 20 inches work travel per tooth, was obtained with these same cutting conditions at room temperatures, when using a highly chlorinated oil.

Face Milling Forged and Resintered Tungsten, 96% Density

Face milling tests were made on forged and resintered tungsten at room temperature and with the workpiece heated to 800°F. These tests were made using a special electric heating furnace mounted on and insulated from the milling machine table. Workpiece temperature was controlled using an autotransformer. A thermocouple was welded to the workpiece, and workpiece temperature was continuously recorded on a strip chart recorder.

The effect of cutting speed in face milling the forged and resintered tungsten at room temperature is shown in Figure 27, page 40. With a grade 883 (C-2) carbide cutter having a 15° negative axial rake and a 0° radial rake, the best tool life, 39 inches of work travel per tooth, was obtained at a cutting speed of 142 feet/minute using a feed of .009 in./tooth with soluble oil cutting fluid. At cutting speeds below and above 142 feet/minute, tool life decreased rapidly. When the workpiece temperature was increased to 800°F, a tool life of less than two inches of work travel was obtained at a cutting speed of 75 feet/minute using a feed of .009 in./tooth.

Figure 28, page 40, shows the effect of feed in face milling forged and resintered tungsten at room temperature. At a feed of .009 in./tooth, the tool life was maximum, 39 inches of work travel per tooth; however, when the feed was reduced to .005 in./tooth, tool life decreased to about six inches of work travel per tooth. At a feed of .014 in./tooth, again only six inches of work travel per tooth was obtained; also, the workpiece chipped badly as the cutter came out of the cut. Backing up the tungsten workpiece with cold rolled steel did not eliminate or even reduce this severe work breakout problem at the .014 in./tooth feed.

End Milling Pressed and Sintered Tungsten, 93% Density

The effect of cutting speed and carbide grade in end mill slotting pressed and sintered tungsten with carbide tipped end mills is shown in Figure 29, page 41. The K-8 grade (C-3) provided much better tool life than the 883 grade (C-2) and 44A grade (C-1) carbides. With the K-8 carbide, a tool life of 45 inches of work travel was obtained at a cutting speed of 200 feet/minute and a feed of .003 inches per tooth.

End Milling Pressed and Sintered Tungsten, 93% Density (continued)

Figure 30, page 41, shows the effect of feed when end mill slotting and peripheral end milling this material. The best tool life, when end mill slotting, was obtained with a feed of .003 in./tooth. The tool life for this feed was 45 inches of work travel. When peripheral end milling pressed and sintered tungsten, the best tool life, 20 inches of work travel, was obtained using a feed of .004 in./tooth.

Increasing the peripheral clearance on the carbide tipped end mill increased the tool life obtained in end mill slotting, Figure 31, page 42. With a 6° clearance angle, the tool life was 17 inches of work travel, compared to 45 inches for the end mill with the clearance angle increased to 12°.

Figure 32, page 42, shows the effect of cutting speed and carbide grade when taking peripheral end milling cuts on pressed and sintered tungsten, 93% density, 34 R_C. The width of cut was 1/4" and the depth 1/8". With a workpiece temperature of 800°F, the best tool life, 109 inches of work travel, was obtained at a cutting speed of 140 feet/minute using a feed of .004 in./tooth and a grade K-8 (C-3) carbide tipped cutter. When the cutting speed was increased to 200 feet/minute, the tool life decreased to about 50 inches of work travel. The workpiece was heated using the electric furnace described in the previous section.

This chart also shows the effect of carbide grade in peripheral end milling this material. A grade K-6 (C-2) carbide tipped cutter gave 99 inches of work travel, while a grade K-11 (C-4) cutter gave 55 inches of work travel at a cutting speed of 140 feet/minute using a feed of .004 in./tooth and a workpiece temperature of 800°F. Figure 32, page 42, also shows the tool life at room temperature. At a cutting speed of 200 feet/minute and a feed of .004 in./tooth, a tool life of 20 inches work travel per tooth was obtained. By comparison, a tool life of 50 inches work travel was obtained when the workpiece temperature was increased to 800°F.

End Milling Forged Tungsten, 96% Density

End milling tests were made using the cutter for slotting forged and resintered tungsten. The results are shown in Figure 33, page 43.

This chart shows the effect of cutting speed, carbide grade and workpiece temperature when using a 1-1/4" diameter carbide tipped end mill with a 0° axial rake and 0° radial rake. Best tool life, 26 inches of work travel, was obtained with a grade K-8 (C-3) carbide tipped cutter operating at a cutting speed of 204 feet/minute, a feed of .003 in./tooth and a soluble oil cutting fluid. Tool life decreased to about five inches of work travel when the cutting speed was reduced to 100 feet/minute or increased to 300 feet/minute.

When a grade K-11 (C-4) carbide tipped end mill was used at 204 feet/minute, a tool life of 13 inches of work travel was obtained. Tool life decreased to seven

End Milling Forged Tungsten, 96% Density (continued)

inches of work travel when a grade 44A (C-1) carbide tipped cutter was used at this cutting speed.

The effect of end mill slotting forged and resintered tungsten at a workpiece temperature of 800°F is also shown. This chart, Figure 33, page 43, shows that when the forged tungsten was heated to 800°F, less than one inch of work travel was obtained using a grade K-11 (C-4) carbide tipped cutter at 204 feet per minute with a feed of .003 in./tooth. The chips were red hot when the cutter began to cut its full width and the test had to be discontinued.

Drilling Pressed and Sintered Tungsten, 96% Density

Initial drilling tests using high speed steel drills proved to be unsatisfactory. Complete point and cutting edge breakdown was evident before drilling one hole. In addition, the cutting forces increased to the point where the workpiece cracked in several pieces. Carbide tipped drills also proved to be unsatisfactory. This type of drill lacked the rigidity for drilling tungsten. Catastrophic failure occurred in each test with no apparent warning. In all tests performed, the carbide tip of the drill failed completely.

With solid carbide drills, it was possible to obtain some drill life. All of the data presented in this report was done with solid carbide twist drills. However, sharpening solid carbide drills presents some additional problems. Not only is a diamond grinding wheel needed, but a very rigid drill grinder is of utmost importance to obtain microscopically chip free cutting edges. Failure to diamond hone the cutting lips of the drill will result in catastrophic failure of the drill with no warning.

Due to the brittle nature of unalloyed tungsten, chipping, flaking and breakout occur quite frequently as the drill enters and when it emerges at the end of the hole. The extreme abrasiveness of this material also causes very rapid wear on the drill, which in turn increases the cutting forces and the tendency to chip and crack.

Figures 34 through 38, pages 43 through 45, present the data obtained when drilling pressed and sintered tungsten of 96% theoretical density, using solid carbide drills.

The effect of cutting speed on drill life is shown in Figure 34, page 43, for feeds of .001 in./rev. and .002 in./rev. The best tool life, seven holes, was obtained using a cutting speed of 150 feet/minute and a feed of .001 in./rev. At this same cutting speed, drill life was reduced to four holes when the feed was increased to .002 in./rev. When the cutting speed was increased above 150 feet/minute or decreased below 150 feet/minute, drill life was again reduced. These data were obtained with a C-2 grade solid carbide, No. 3 (.213") diameter twist drill, using highly chlorinated oil as the cutting fluid.

Drilling Pressed and Sintered Tungsten, 96% Density (continued)

Figure 35, page 44, shows the effect of feed when drilling this material at a cutting speed of 150 feet/minute. Maximum drill life, seven holes, was obtained at a feed of .001 in./rev. When the feed was decreased to .0005 in. per rev., drill life dropped to six holes. When the feed was increased to .002 in./rev., four holes were drilled, and with a feed of .005 in./rev. only two holes could be drilled.

Figure 36, page 44, shows the effect of clearance angle when drilling this material at 150 feet/minute with a .001 in./rev. feed. Drill life was the same, four holes, when a clearance of 5° and of 7° was used. When the clearance was reduced to 3°, drill life dropped to two holes. These tests were run with a plain 118° point angle so that lip clearance could be measured accurately.

The effect of drill helix angle is shown in Figure 37, page 45. A straight flute solid carbide 0° helix angle drill provided a drill life of three holes, while a twist drill with a 29° helix angle provided a drill life of seven holes.

Figure 38, page 45, shows the effect of the cutting fluid when drilling this pressed and sintered tungsten with solid carbide drills. Maximum drill life, eight holes, was obtained using highly chlorinated oil applied as a flood. When a highly chlorinated oil was applied in a spray mist, drill life was reduced to three holes. Soluble oil, highly sulphurized oil and water soluble wax cutting fluids applied as a flood and spray mist provided a drill life of only two holes.

A series of tests were made to compare the effect of different processing techniques on drill life when drilling unalloyed tungsten. In addition to 93% density pressed and sintered tungsten, forged and subsequently resintered tungsten and arc cast tungsten were drilled. Using .213" diameter grade 883 (C-2) solid carbide drills, Figure 39, page 46, shows the best drill life was 15 holes obtained in the forged and resintered tungsten at a cutting speed of 150 feet/min. at a feed of .002 in./rev. With these drilling conditions, a drill life of 12 holes was obtained in the pressed and sintered material and nine holes in the arc cast tungsten. Very little work breakout was observed in the workpiece when the drill emerged through in the arc cast tungsten. The breakout problem was more severe when drilling the forged and pressed and sintered tungsten.

Drilling Pressed and Sintered Tungsten, 93% Density, at Elevated Temperature

In drilling pressed and sintered tungsten at elevated temperatures, it was noted that blowing a stream of air at 20 psi on the drill increased drill life. Also, when powdered molybdenum disulphide (MoS_2) was added to the air stream using an aspirator, drill life was increased over that obtained with plain air. Approximately one-half ounce of MoS_2 was used to drill one hole, see Figure 40, page 46.

A drill life of three holes was obtained at a cutting speed of 150 feet/minute on

Drilling Pressed and Sintered Tungsten, 93% Density, at Elevated Temperature (continued)

the tungsten heated to 400°F using air. With a powdered MoS_2 added to the air stream, drill life was increased to seven holes. However, the MoS_2 powder introduced a serious cleaning problem and a health hazard to the operator. These tests were made using the electric furnace described previously.

Figure 41, page 47, shows the effect of feed in drilling this pressed and sintered tungsten heated to 400°F at a speed of 150 feet/minute with C-2 (883) grade solid carbide drills. A feed of .002 in./rev. produced better drill life than a feed of .001 or .005 in./rev. Here, air alone was used to clear the chips from the drill.

A short series of tests made at 400°F indicated that higher cutting speeds produced better drill life, Figure 42, page 47. Drill life was increased from four holes at 100 feet/minute to ten holes at 200 feet/minute in drilling 1/2" deep through holes with a .213" diameter C-2 (883) grade solid carbide drill. Air plus molybdenum disulphide powder was used as a "cutting fluid."

The effect of workpiece temperature in drilling pressed and sintered tungsten, 93% theoretical density, 26 R_c, is shown in Figure 43, page 48. When the workpiece temperature was increased, drill life increased. Drill life at 200 feet/minute with the C-2 (883) grade solid carbide drill was only five holes at room temperature, compared with 27 holes at 800°F.

Drilling Pressed and Sintered Tungsten Sheet Material

The results of the drilling tests on tungsten sheet are shown in Figures 44 and 45, pages 48 and 49.

Figure 44, page 48, shows the effect of cutting speed and feed in drilling pressed and sintered 45 R_c tungsten sheet 1/16" thick with 1/8" diameter grade 883 (C-2) solid carbide drills. Best drill life, 30 holes, was obtained at a cutting speed of 250 feet/minute with a feed of 2.25 in./min. or .0003 in./rev. (7640 rpm). When the feed was reduced to 1.5 in./min. or .0002 in./rev., drill life decreased to 12 holes and when the feed was increased to .0008 in./rev., drill life decreased to less than five holes. These tests were performed with a 90° point angle drill with a notched point. Delamination at the edge of the hole was observed on the bottom side of the workpiece.

The effect of sheet thickness is shown in Figure 45, page 49. This chart shows that drill life is increased some sixfold when 1/16" thick sheet is drilled, compared with drilling 1/8" thick sheet tungsten, using 1/8" diameter solid carbide drills. At a cutting speed of 250 feet/minute with a feed of .0003 in./rev., 30 holes were drilled in 1/16" thick sheet, while five holes were drilled in 1/8" thick sheet material with a 90° point angle drill. The quality of the holes drilled through the 1/16" thick sheet was good until the drill dulled, after which delamination occurred.

Tapping Pressed and Sintered Tungsten, 96% Density

The results of the tapping tests on pressed and sintered tungsten, 96% density, 34 R_C, are presented in Figures 46 through 50, pages 49 through 52.

In tapping 1/2" through holes using 5/16-24 NF, 4 flute plug stub taps, Figure 46, page 49, shows the effect of workpiece temperature. A tap life of 14 holes was obtained when the workpiece was held at 400°F, 600°F, and 800°F. When the workpiece temperature was decreased to 200°F, the tap life decreased to eight holes, and with the workpiece at room temperature only two holes could be tapped. The elevated temperature tests were made using the electric furnace described previously.

Figure 47, page 50, shows the effect of cutting speed in tapping pressed and sintered tungsten at 600°F using 5/16-24 NF standard taps. Maximum tap life of 13 holes was obtained at a cutting speed of 5.3 feet/minute. When the cutting speed was increased to 15 feet/minute, tap life decreased to one hole.

The effect of workpiece temperature and tap design is shown in Figure 48, page 50. Fourteen holes could be tapped on the pressed and sintered tungsten when the workpiece temperature was increased to 800°F using a stub type tap. With a standard length tap, only six holes were tapped. Tests performed at room temperature showed that a stub length tap and standard length tap provided two holes.

Figure 49, page 51, shows a photograph of the special stub tap used for these tests and a standard length 4 flute tap. The overall length of the stub tap is two inches, compared to 2-3/4 inches overall length for the standard tap. The flute length of the stub is 1/2". The maximum depth through hole that can be tapped is 9/16". This stub design provides greater rigidity which is necessary in tapping tungsten.

The effect of percent thread is shown in Figure 50, page 52. This chart shows very little difference in tap life when a 60% and 75% thread is tapped. Three 60% holes were tapped in the pressed and sintered tungsten, while two 75% holes were obtained using a 5/16-24 NF standard length tap operating at 5.3 feet per minute with a highly chlorinated oil.

Grinding Pressed and Sintered Tungsten, 93% Density

Until recently, there appeared to be a reluctance toward using grinding in the industry because of the tendency of grinding to produce surface cracks and high residual stresses. The cracking tendency and the high residual stresses are undoubtedly accentuated by the use of conventional grinding conditions. The grinding investigation has shown that it is possible to grind tungsten and not produce cracks or unusually high residual stresses if low stress conditions are employed. The surface finishes obtained ranged from 10 to 40 microinches, depending upon the specific grinding variables used. However, the grinding ratios, in general, were low.

Grinding Pressed and Sintered Tungsten, 93% Density (continued)

The results of the grinding tests on the pressed and sintered tungsten, 93% density, 26 R_C, are shown in Figures 51 through 58, pages 52 through 56.

The effect of wheel grade, wheel speed and grinding fluid in grinding tungsten is shown in Figure 51, page 52. The best G ratio, 4.4, was obtained with a 32A46N5VBE wheel operating at a wheel speed of 4000 feet/minute using a 5% potassium nitrite solution (KNO_2) as a grinding fluid. With soluble oil and highly sulphurized oil and softer grades of wheels, the maximum G ratio that could be obtained was about three.

Figure 52, page 53, shows that at the lower down feed of .0005 in./pass a G ratio of 5.2 was obtained with the 32A46N5VBE wheel at a wheel speed of 2000 feet/minute using a 5% KNO_2 solution as the grinding fluid.

Surface grinding data on pressed and sintered tungsten of 93% theoretical density is presented in Figures 53 through 58, pages 53 through 56, using a highly sulphurized grinding oil. These results were obtained before the 5% KNO_2 solution was used.

The effect of wheel grade on grinding ratio is shown in Figure 53, page 53. Using a wheel speed of 2000 feet/minute, a table speed of 40 feet/minute, a cross feed of .050 in./pass and a down feed of .001 in./pass, a G ratio of approximately three was obtained with a 46 grit, "N" hardness, 5 structure wheel. However, chatter was encountered under these conditions. Changing the wheel hardness from "N" to "L" did not eliminate the chatter, but reduced the G ratio to less than two. Use of "J" and "K" hardness wheels did eliminate the chatter condition, but provided a G ratio of only slightly over one.

Figure 54, page 54, shows the effect of wheel speed on the grinding ratio for two different wheel grades when surface grinding the tungsten material. A grinding ratio of approximately three was obtained with an "N" grade wheel at 2000 feet/minute. When the wheel speed was increased to 6000 feet/minute, the grinding ratio was reduced to about one. No significant difference in grinding ratio was observed when using a highly sulphurized oil or a soluble oil grinding fluid. However, surface cracks were produced on the workpiece when the soluble oil was used.

Little difference in the grinding ratio was observed when the table speed was varied between 20 and 60 feet/minute, see Figure 55, page 54. With an "N" grade wheel operating at 2000 feet/minute, the grinding ratio varied from 2-1/2 to 3, when the table speed was changed from 20 to 60 feet/minute.

Figure 56, page 55, shows the effect of down feed when surface grinding the tungsten material. With an "N" grade wheel at a wheel speed of 2000 feet per minute, the G ratio was reduced from three to two when the down feed was

increased from .0005 to .002 in./pass. Chatter marks and surface cracks were observed on the workpiece when using the .002 in./pass down feed.

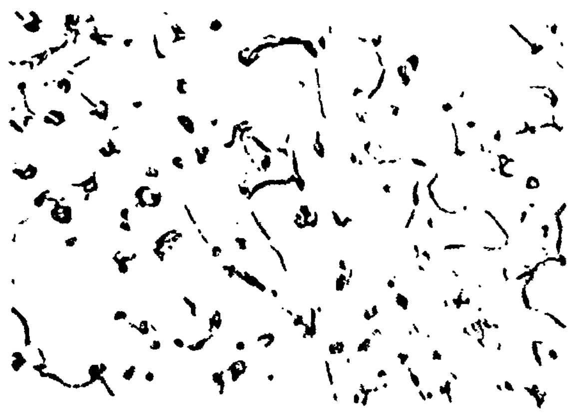
No significant change in G ratio was observed when the cross feed was varied from .025 to .100 in./pass for grade "L" and "N" wheels operating at 2000 feet/minute, see Figure 57, page 55.

The effect of grinding fluid is shown in Figure 58, page 56, when surface grinding unalloyed pressed and sintered tungsten with three different grades of wheels. For a given hardness wheel, the grinding ratio did not change significantly when using a highly sulphurized oil, a highly chlorinated oil or a soluble oil. With the harder grade "N" wheel, a G ratio of approximately three was produced with all three grinding fluids. However, surface cracks and chatter marks were present on the workpiece when soluble oil was used.

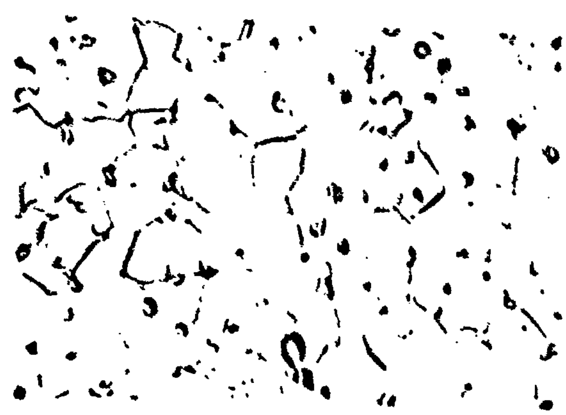
The grinding recommendations given in Table 2, page 31, were selected to reduce the tendency for surface cracking and workpiece distortion. Section XI of this report presents the data on workpiece distortion and residual stresses in grinding unalloyed tungsten.

Microstructures of Pressed and Sintered Tungsten

Density: 85%
Hardness: 90 R_B



Density: 93%
Hardness: 32-34 R_c



Density: 96%
Hardness: 34 R_c

All materials show homogeneous, fine grained matrix with no appreciable microstructural differences.

Magnification: 1000X   Etchant: Murikami's

Figure 10

See Text, page 15

Electron Photomicrograph of Pressed and Sintered Tungsten

Density: 96%
Hardness: 34 R_c

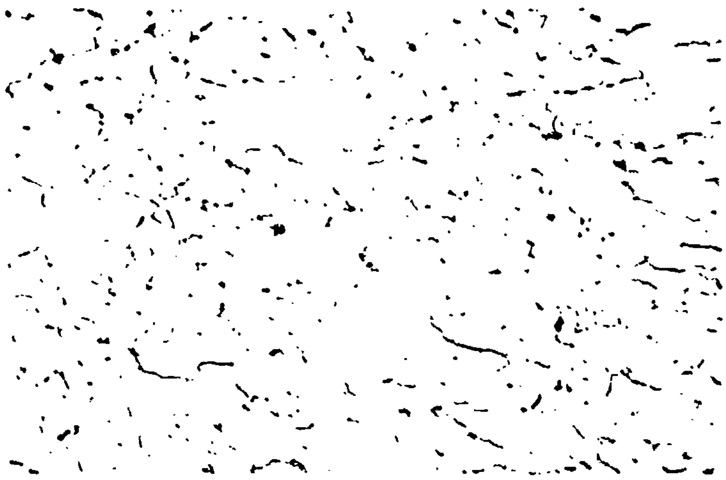
Uniform equiaxed grains showing small voids typical of pressed and sintered tungsten at this density level.

Magnification: 13,000X   Etchant: Electrolytic

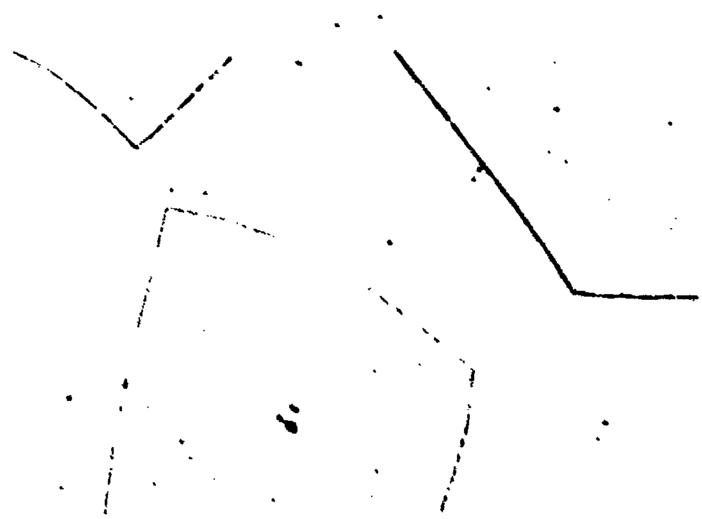
Figure 11

See Text, page 15

Microstructure of Forged and Cast Tungsten



Forged Tungsten at
96% of theoretical density and 35 R_c
Grain structure somewhat elongated as a result of forging operation.
Magnification: 500X Etchant: Murikami's



Arc Cast Tungsten at
99% of theoretical density and 31 R_c
Large, essentially equiaxed grain structure.
Magnification: 100X Etchant: Murikami's

Figure 12

See Text, page 15

TABLE 2

RECOMMENDED CONDITIONS FOR MACHINING AND GRINDING UNALLOYED TUNGSTEN

	Nominal Chemical Composition, Percent							
	O	N	C	Mo	Mn	Si	Co	W
Pressed and Sintered	.005	.002	.010	.02	.001	.01	.01	Bal.
Forged and Resintered	.005	.001	.010	.02	.001	.01	.01	Bal.
Arc Cast	.002	.001	.004	.50	--	--	--	Bal.

Operation	Tool Material	Tool Geometry	Tool Used for Tests	Depth of Cut inches	Width of Cut inches	Feed	Cutting Speed ft./min	Tool Life	Wear-land inches	Cutting Fluid
Turning Pressed & Sintered 93% Density 32-34 Rc	C-4 Carbide	BR: -15° SCEA: 15° SR: 0° ECEA: 15° Relief: 5° NR: 1/32"	5/8" square brazed tool bit	.050	---	.009 in/rev	200	15 min.	.030	Soluble Oil (1:20)
Face Milling Pressed & Sintered 85% Density 90 Rb	C-4 Carbide	AR: 0° RR: 0° CA: 45° Clearance: 15°	4" Diameter single tooth face mill	.060	2	.012 in/tooth	100	70 in/tooth	.016	Highly Chlorinated Oil
Face Milling Pressed & Sintered [illegible] Density [illegible]	C-4 Carbide	AR: -15° RR: 0° CA: 45° Clearance: 15°	4" diameter single tooth face mill	.060	1-1/4	.010 in/tooth	78	27 in/tooth	.030	Highly Chlorinated Oil
Face Milling Forged & Resintered 96% Density 35 Rc	C-2 Carbide	AR: -15° RR: 0° CA: 45° Clearance: 15°	4" diameter single tooth face mill	.060	1-1/2	.009 in/tooth	142	39 in/tooth	.030	Soluble Oil (1:20)
End Mill Slotting P&S 93% Density 34 Rc	C-3 Carbide	AR: 0° RR: 0° CA: 45° x .060 Clearance: 12°	1-1/4" diameter 4 tooth carbide tipped end mill	.125	1.250	.003 in/tooth	200	45 inches	.030	Soluble Oil (1:20)
Peripheral End Milling P&S, 35 Rc 93% Density	C-3 Carbide	AR: 0° RR: 0° CA: 45° x .060" Clearance: 12°	1-1/4" diameter 4 tooth carbide tipped end mill	.125	.250	.004 in/tooth	140	110 inches	.030	End milling done with workpiece temperature of 800° F

See Text, page 16

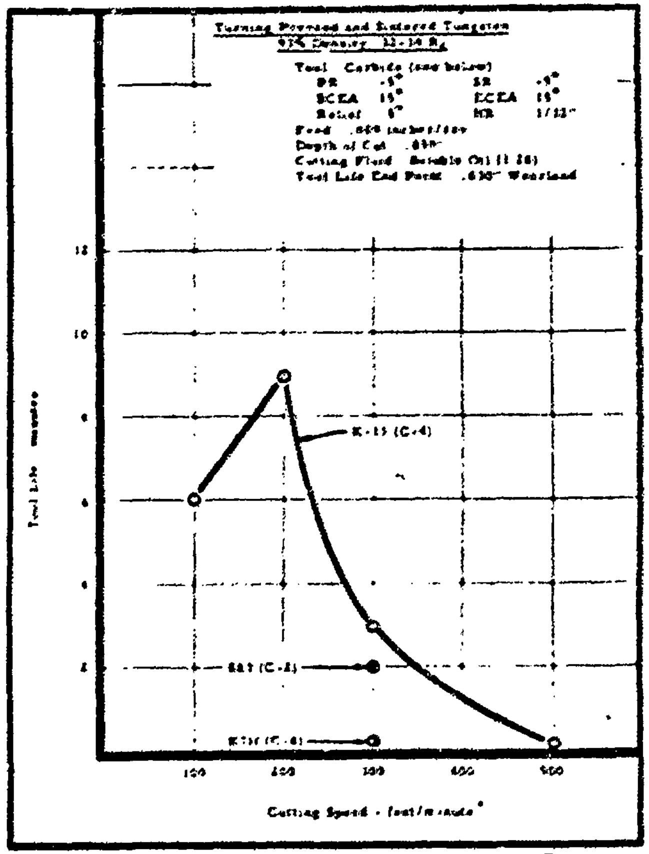
TABLE 2 (continued)
RECOMMENDED CONDITIONS FOR MACHINING AND GRINDING UNALLOYED TUNGSTEN

Operation	Tool Material	Tool Geometry	Tool Used for Tests	Depth of Cut inches	Width of Cut inches	Feed	Cutting Speed ft./min	Tool Life	Wear-land inches	Cutting Fluid
End Mill Slotting F&R 96% Density 35 R_c	C-3 Carbide	AR: 0° RR: 0° CA: 45° x .060" Clearance: 12°	1-1/4" diameter 4 tooth carbide tipped end mill	.125	1.250	.003 in/tooth	200	26 inches	.030	Soluble Oil (1:20)
Drilling Pressed & Sintered 93% Density 34 R_c	C-2 Carbide	118°/90° notched point 7° clearance	.213" diameter 29° helix angle solid carbide drill	1/2" thru	---	.002 in/rev	125	14 holes	.030	Highly Chlorinated Oil
Drilling Forged & Resintered 96% Density 35 R_c	C-2 Carbide	118°/90° notched point 7° clearance	.213" diameter 29° helix angle solid carbide drill	1/2" thru	---	.002 in/rev	150	15 holes	.030	Highly Chlorinated Oil
Drilling Arc Cast [illegible]% Density [illegible] R_c	C-2 Carbide	118°/90° notched point 7° clearance	.213" diameter 29° helix angle solid carbide drill	1/2" thru	---	.002 in/rev	150	9 holes	.030	Highly Chlorinated Oil
Tapping Pressed & Sintered 96% Density 34 R_c	M-10 HSS	4 flute special stub type plug tap, 75% thread	5/16-24 NF	1/2" thru	---	---	5	14 holes	---	Tapping done with work-piece temperature of 400°F

SURFACE GRINDING

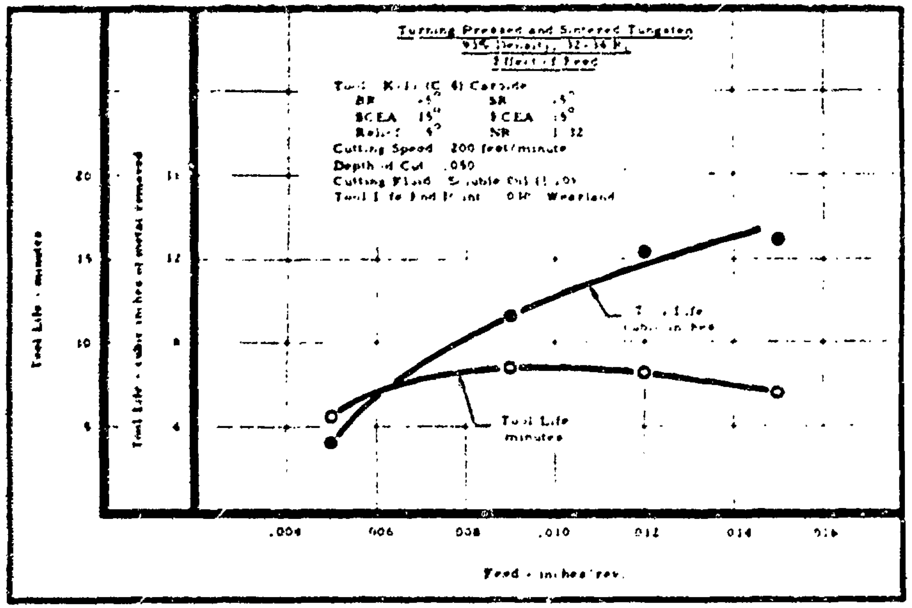
Wheel Grade	Grinding Fluid	Wheel Speed feet/minute	Table Speed feet/minute	Down Feed inches/pass	Cross Feed inches/pass	G Ratio
32A46N5VBE	KNO_2 Solution	2000	40	.0005	.050	5.0
32A46N5VBE	Highly Sulphurized Oil	2000	40	.0005	.050	2.5

See Text, page 16



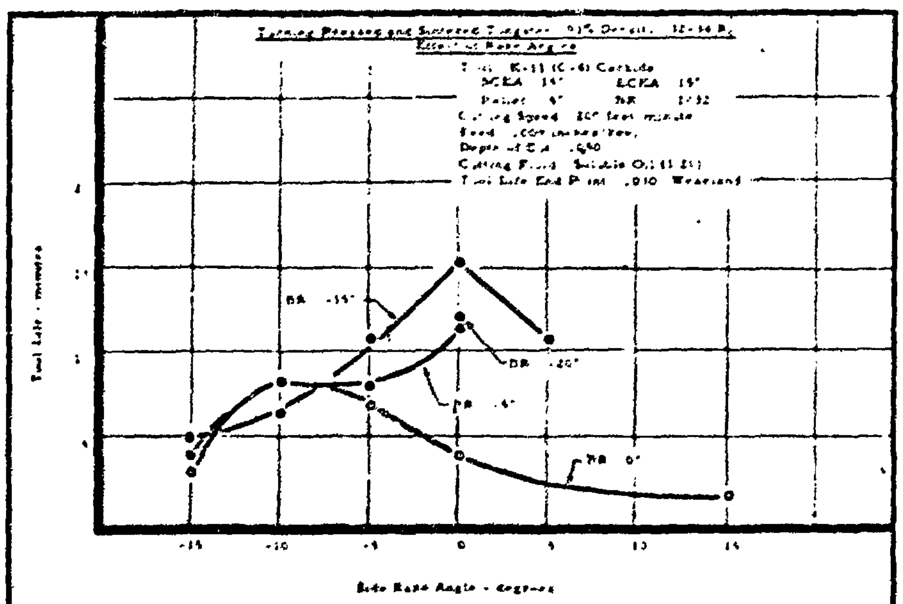
See Text, page 16

Figure 13



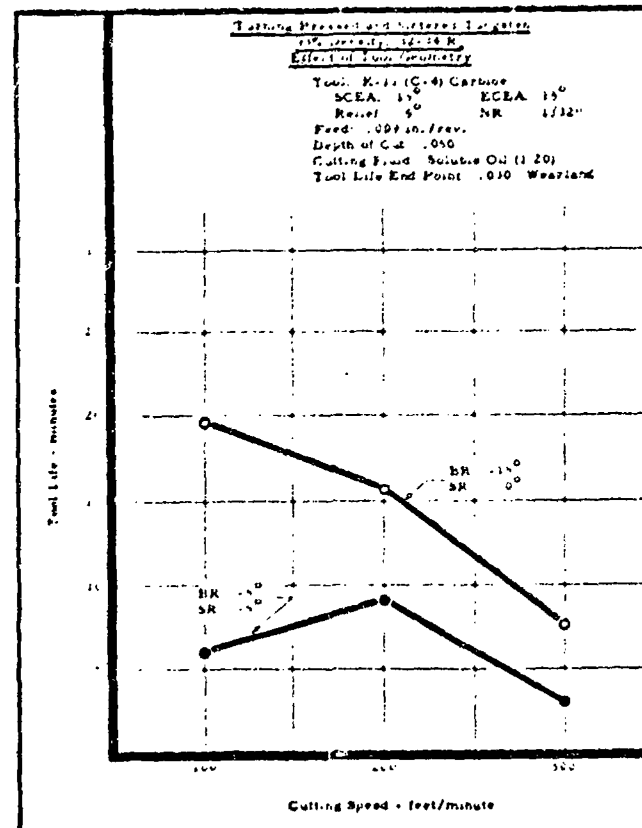
See Text, page 16

Figure 14



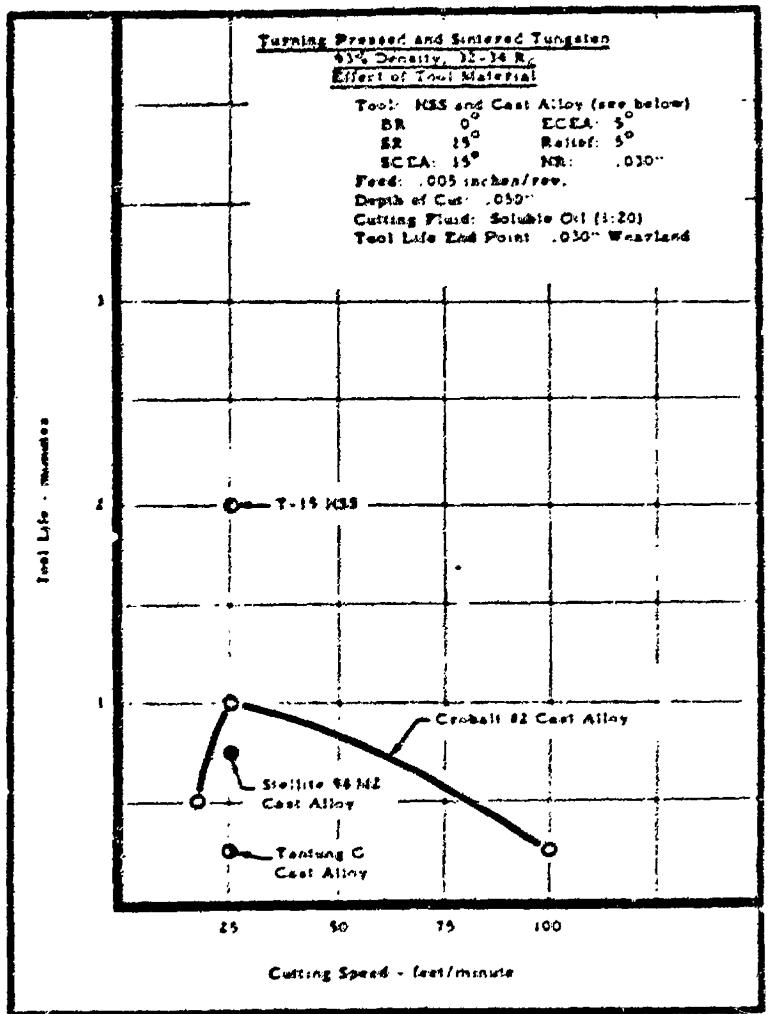
See Text, page 16

Figure 15



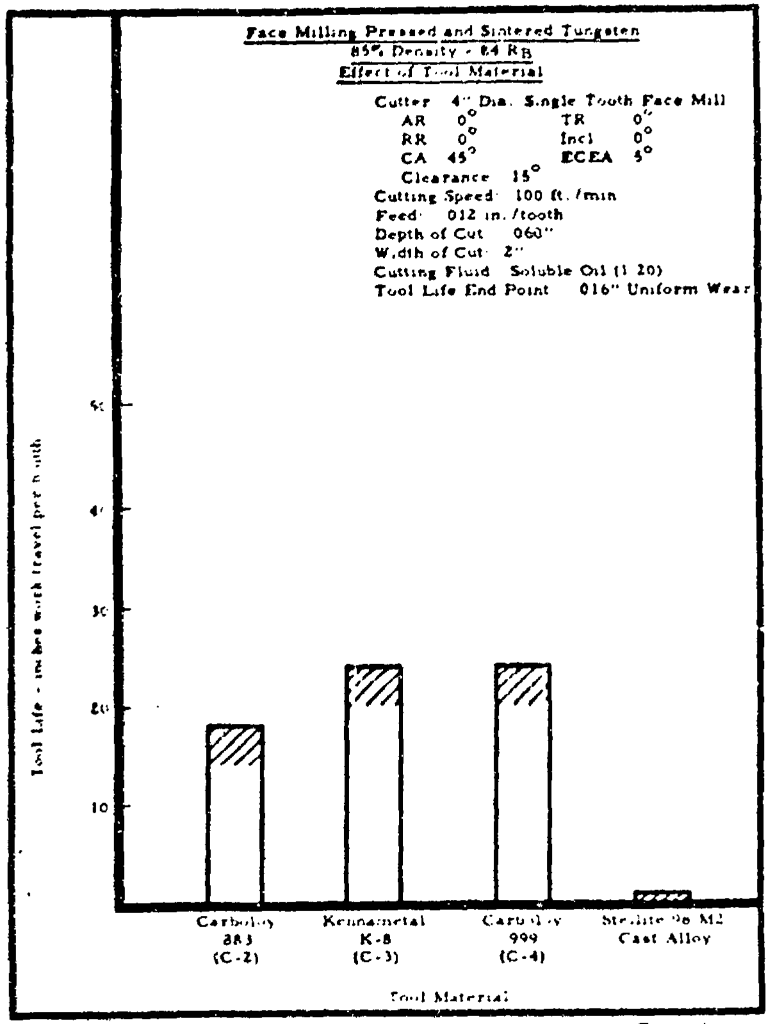
See Text, page 17

Figure 16



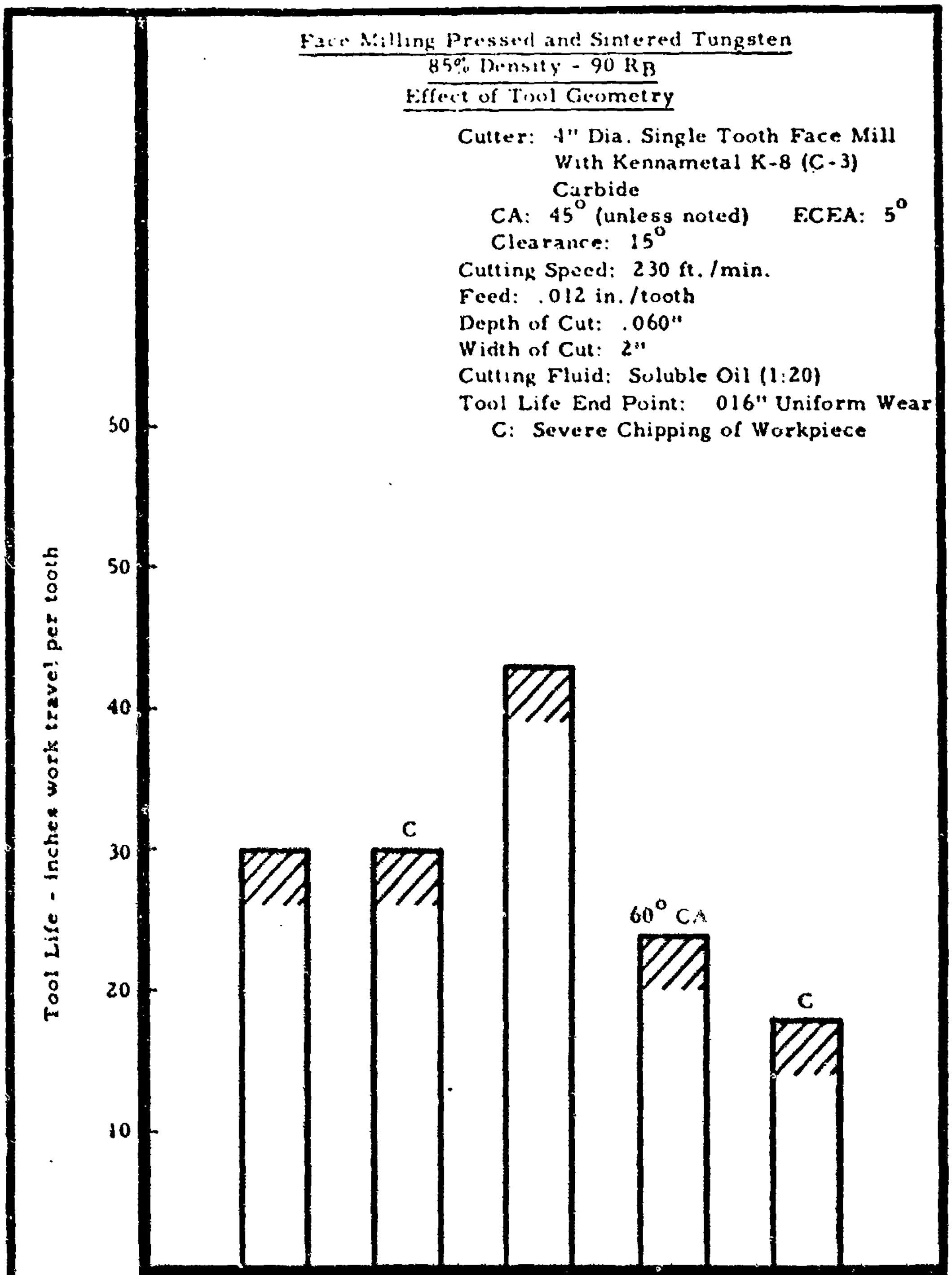
See Text page 17

Figure 17



See Text, page 17

Figure 18



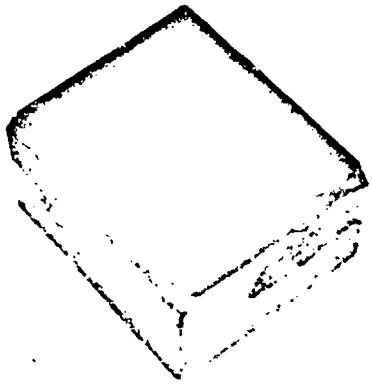
Axial Rake	7	0	0	0	0
Radial Rake	7	15	0	0	-15
Resultant Rake	10	10	0	0	-10
Inclination	0	-10	0	0	10

Tool Angles - degrees

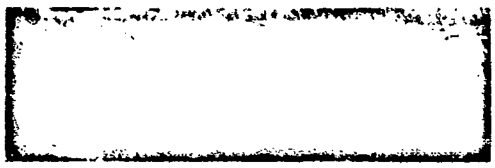
See Text, page 17

Figure 19

Illustrations of Work Breakout in Machining Unalloyed Tungsten



Breaking and chipping at the edges of the workpiece in face milling



Chipping and flaking produced in drilling. The above view is the top of the holes. The photo below shows the condition of the workpiece after the drill emerged from the holes.

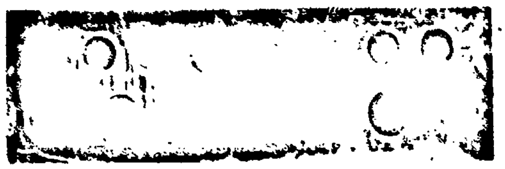
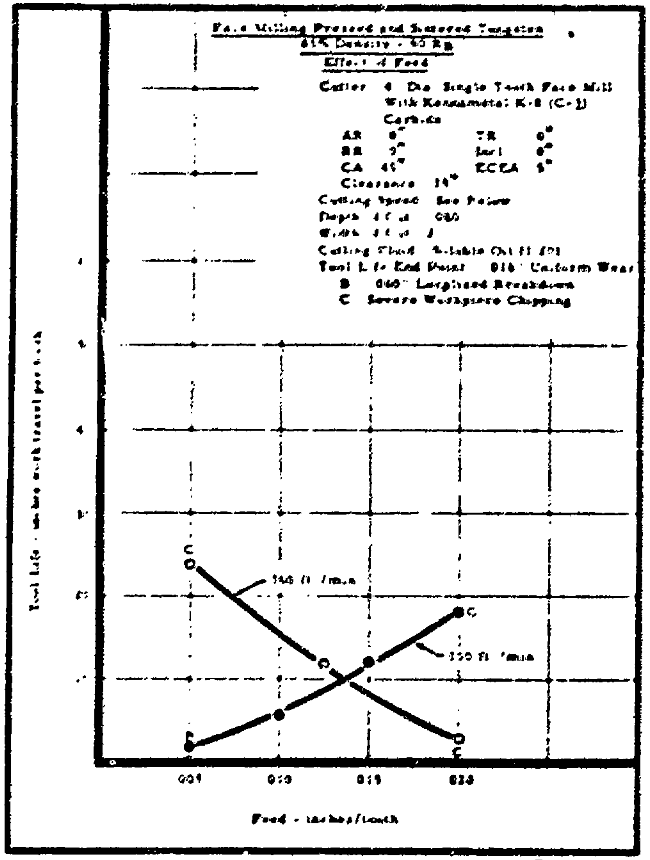


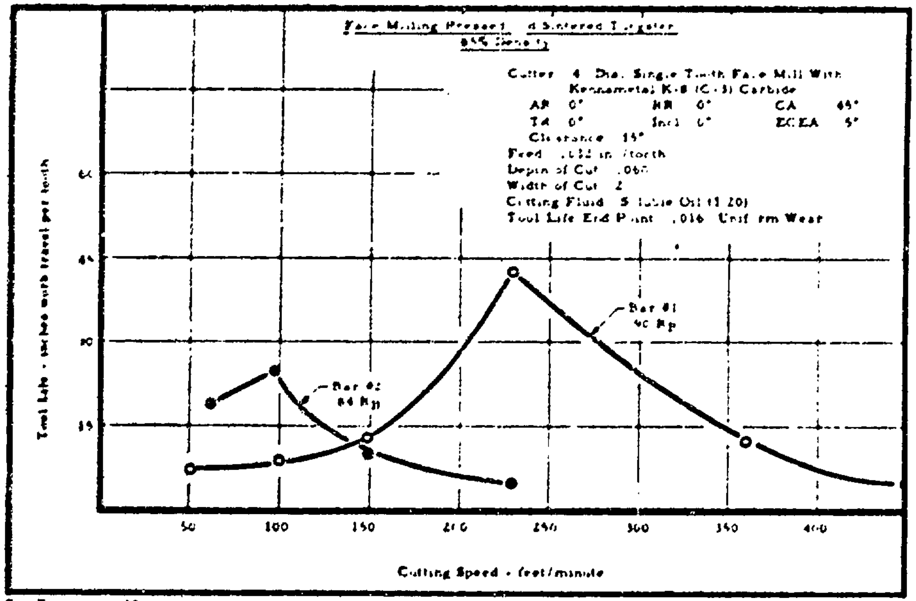
Figure 20

See Text, page 17



See Text, page 17

Figure 21



See Text, page 18

Figure 22

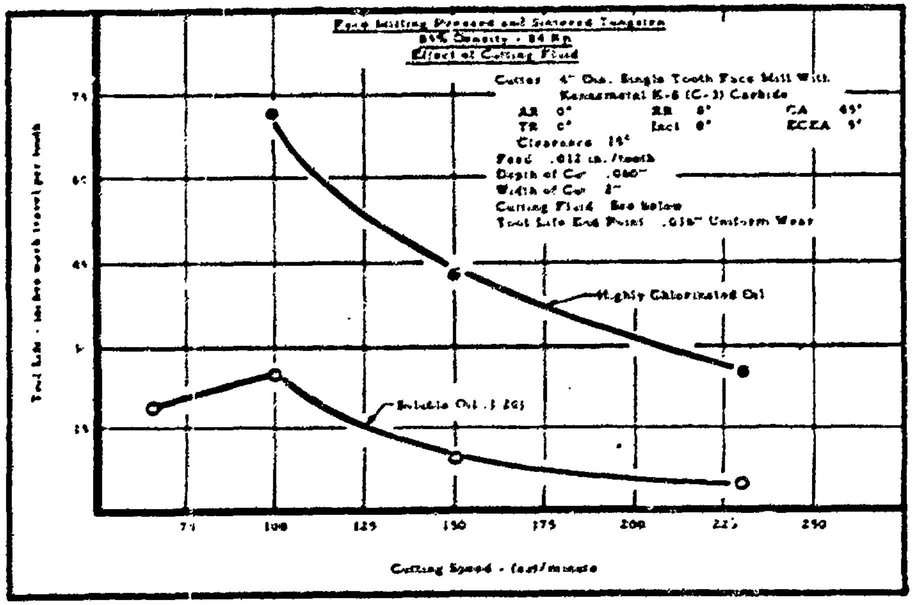


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Figure 23

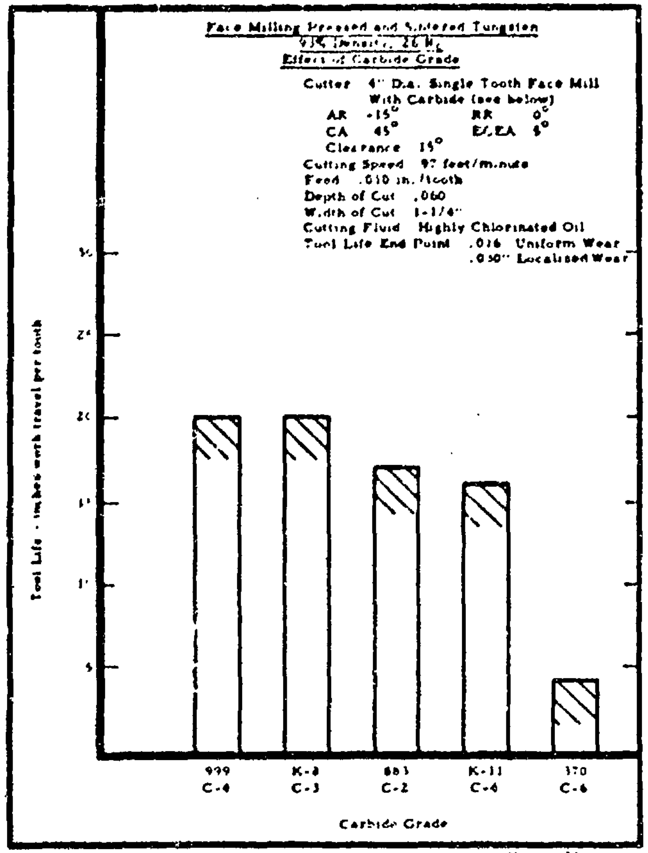

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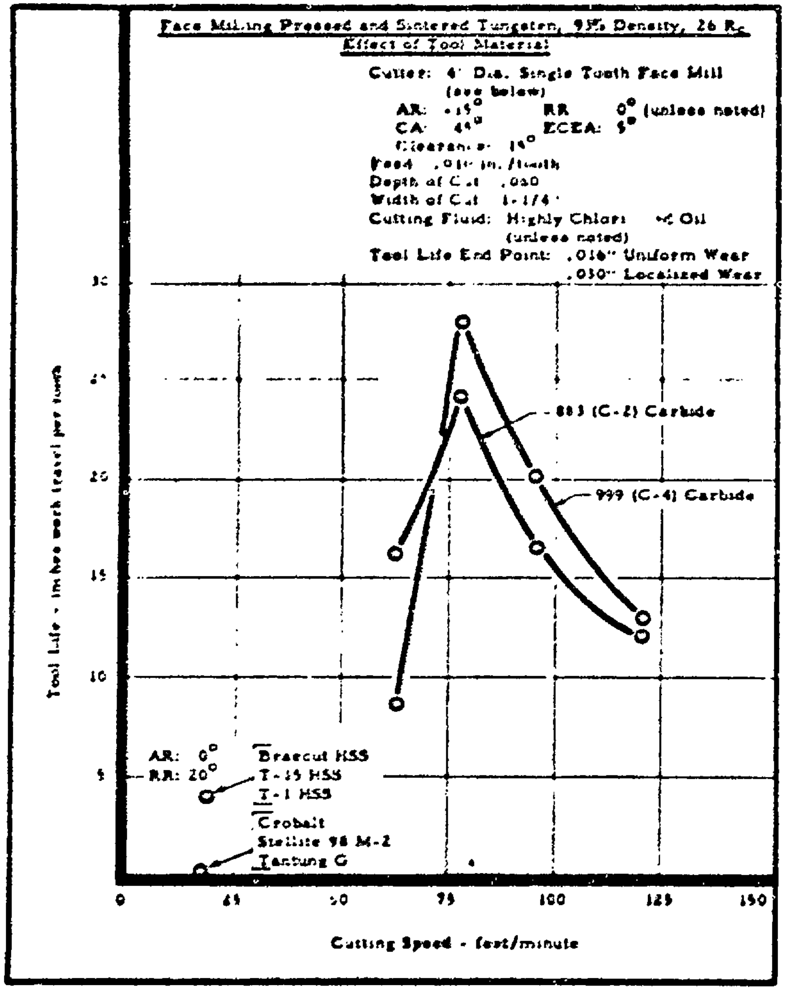
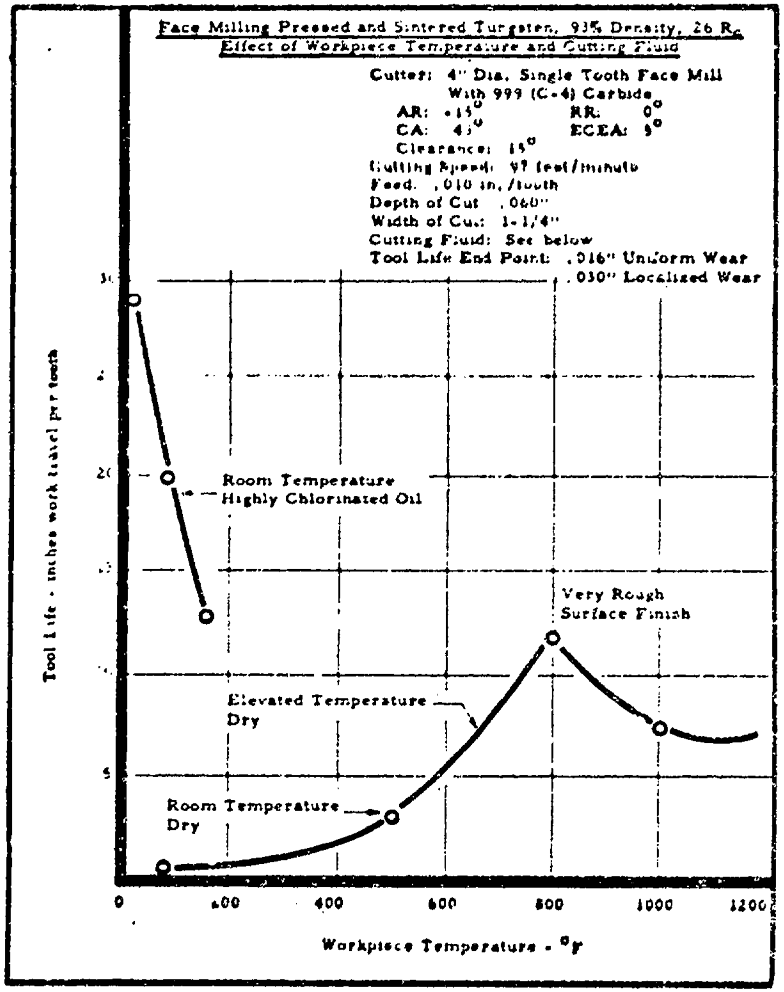
Figure 24



See Text, page 18

Figure 25



See Text, page 18

Figure 26

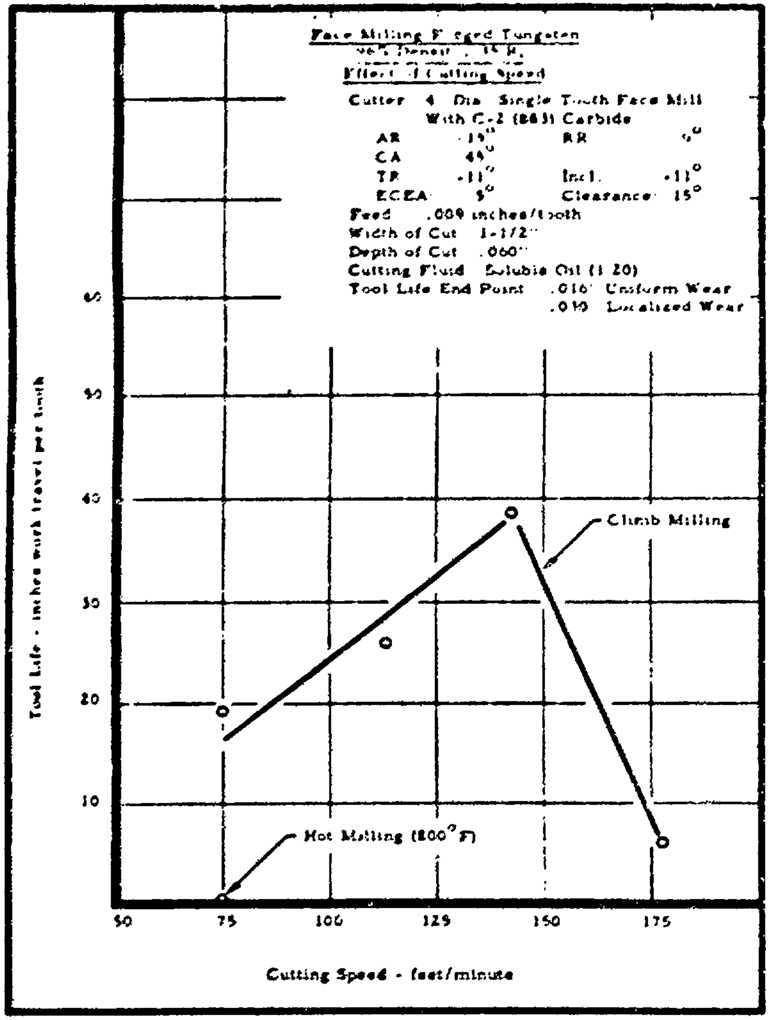


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Figure 27

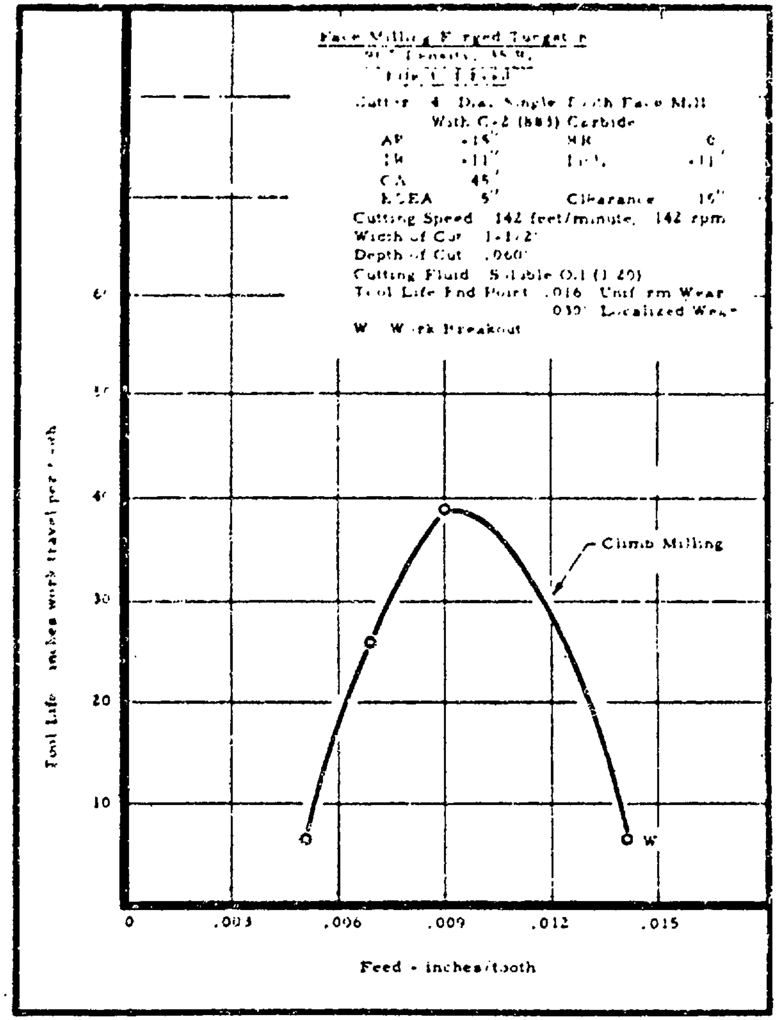

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Figure 28

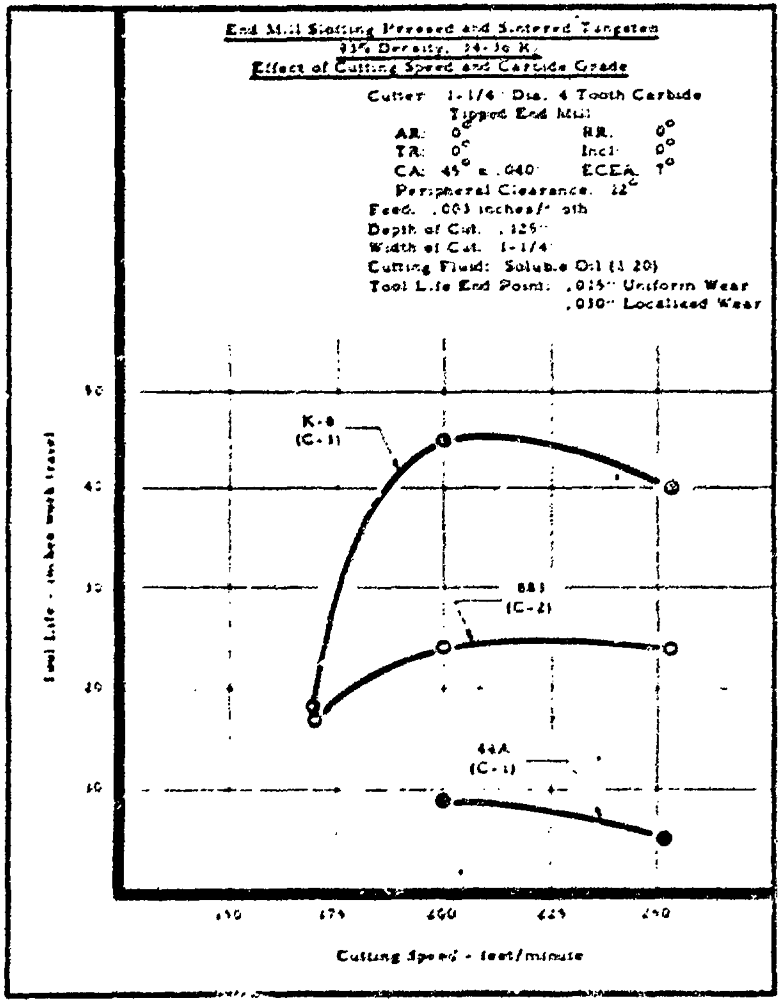

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Figure 29

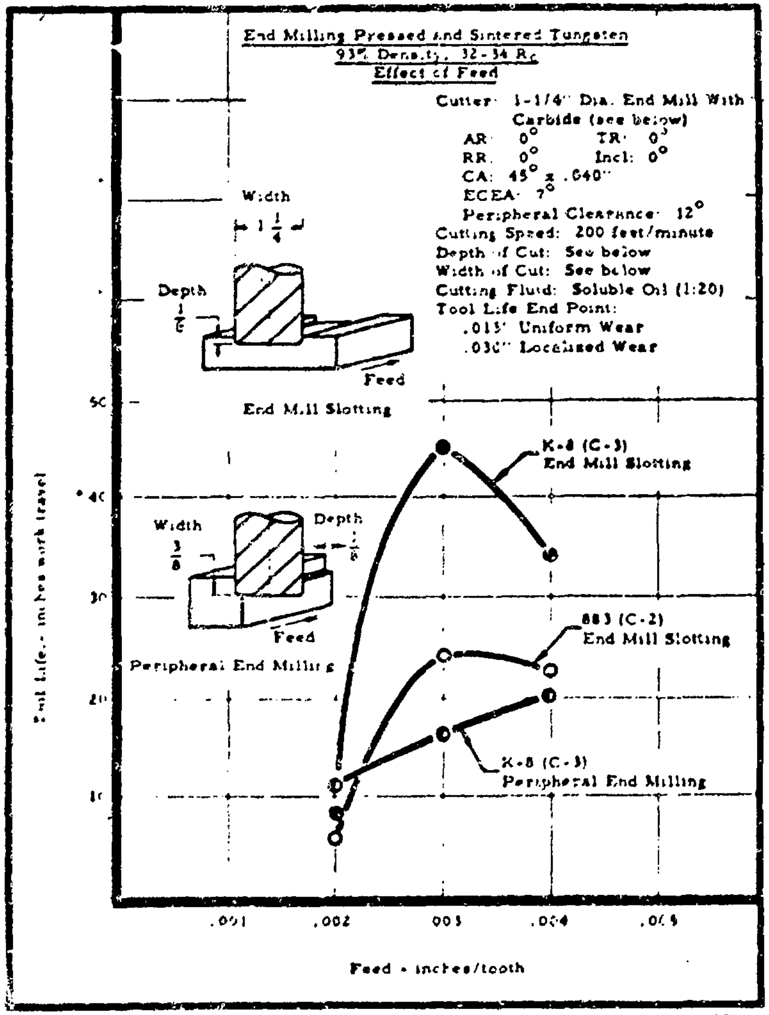

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Figure 30

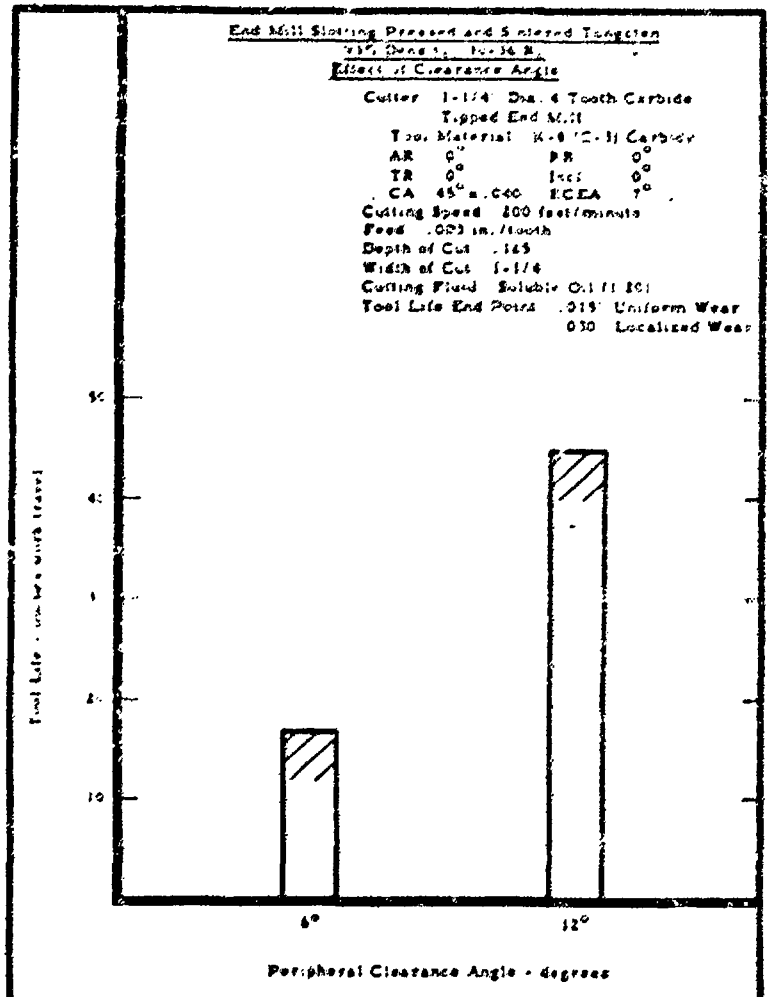

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Figure 31

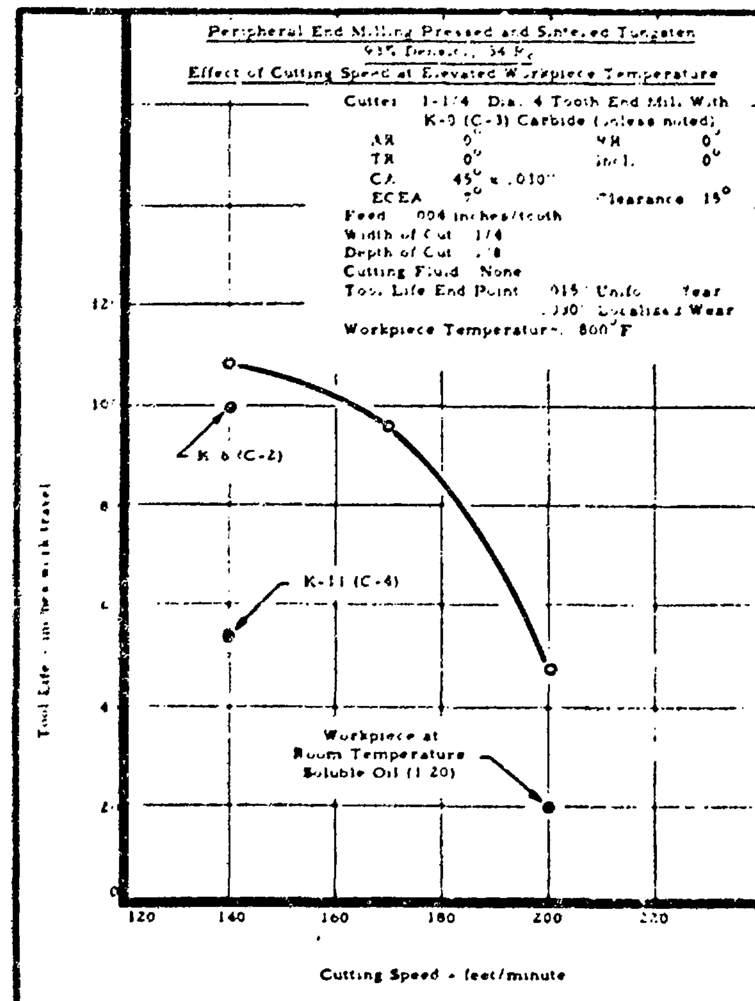

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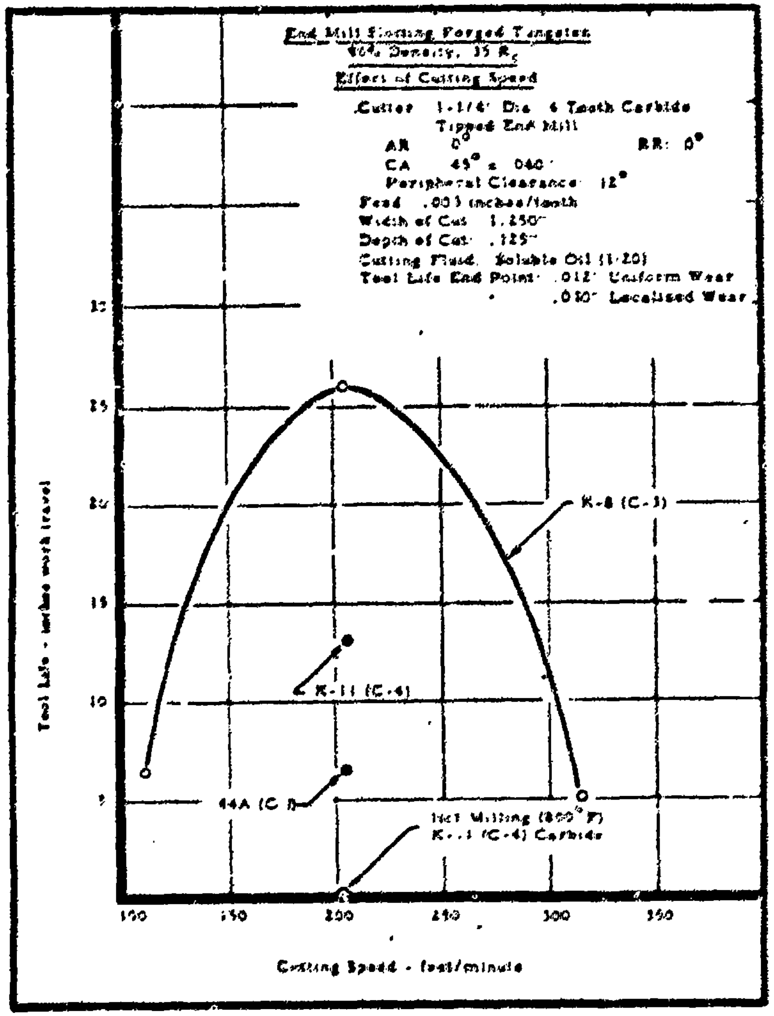
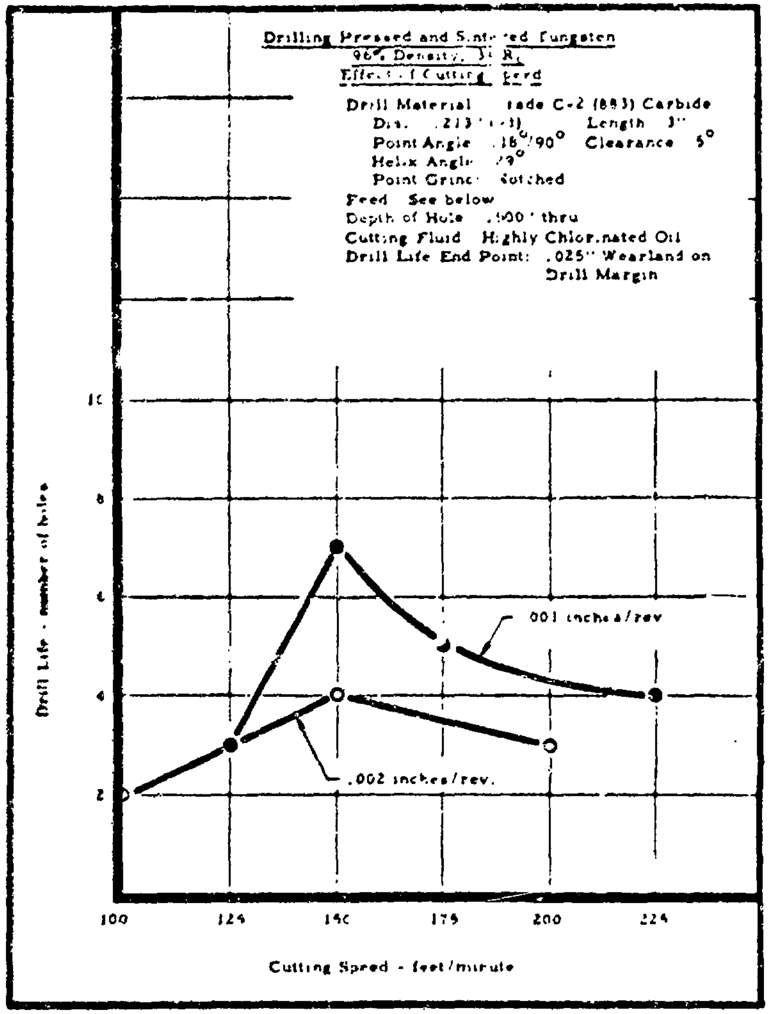
Figure 32



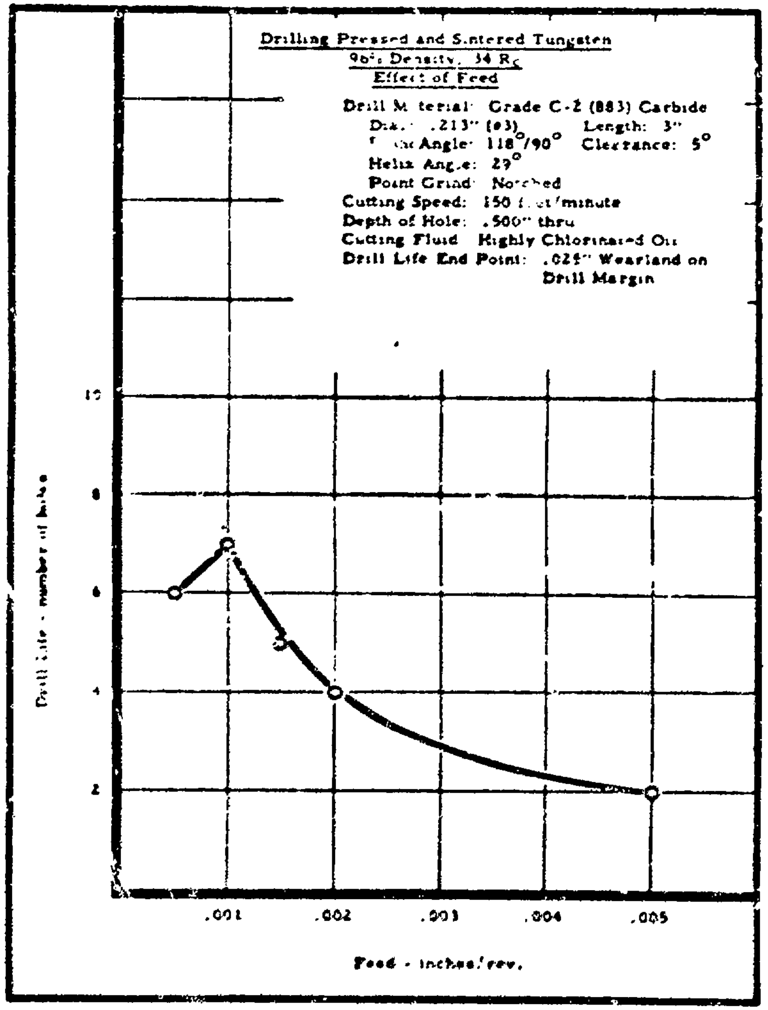
See Text page 20

Figure 33



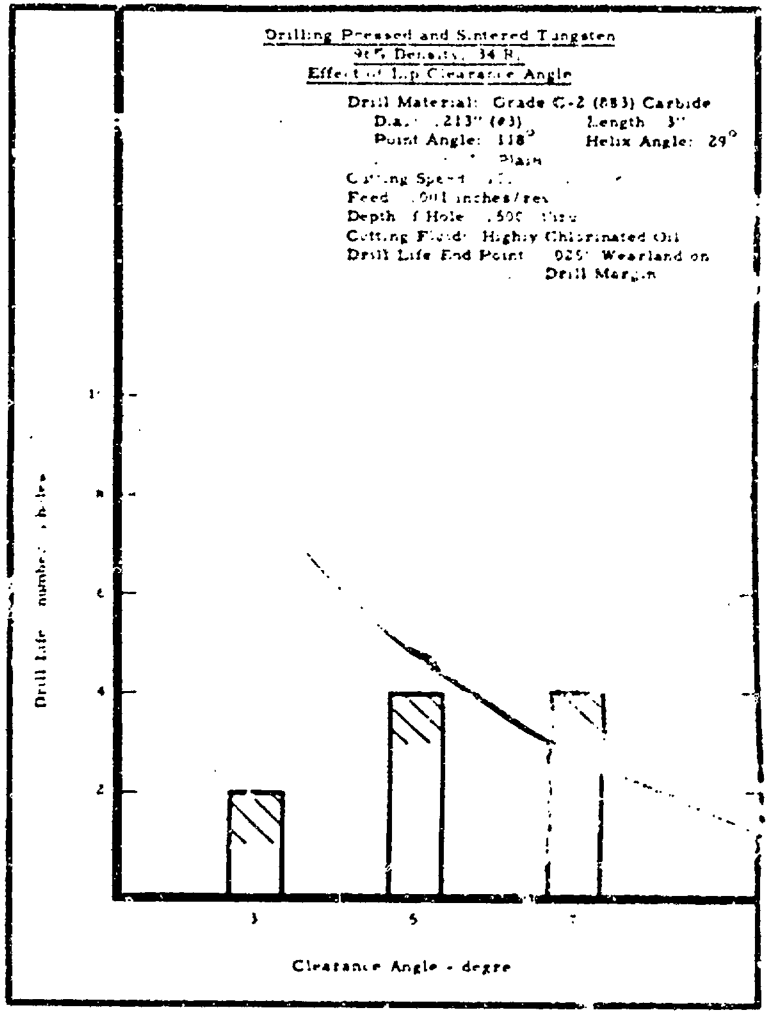
See Text, page 21

Figure 34



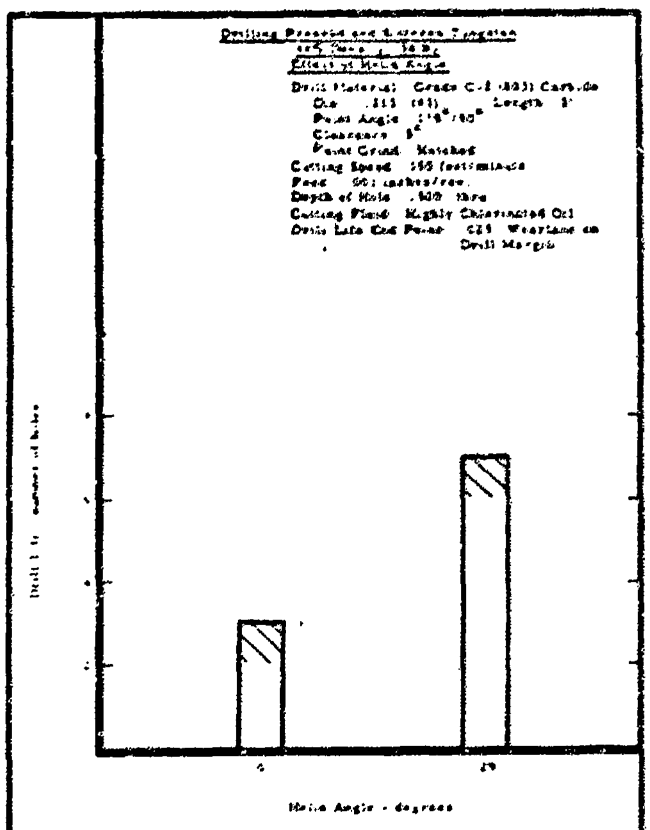
See Text, page 22

Figure 35



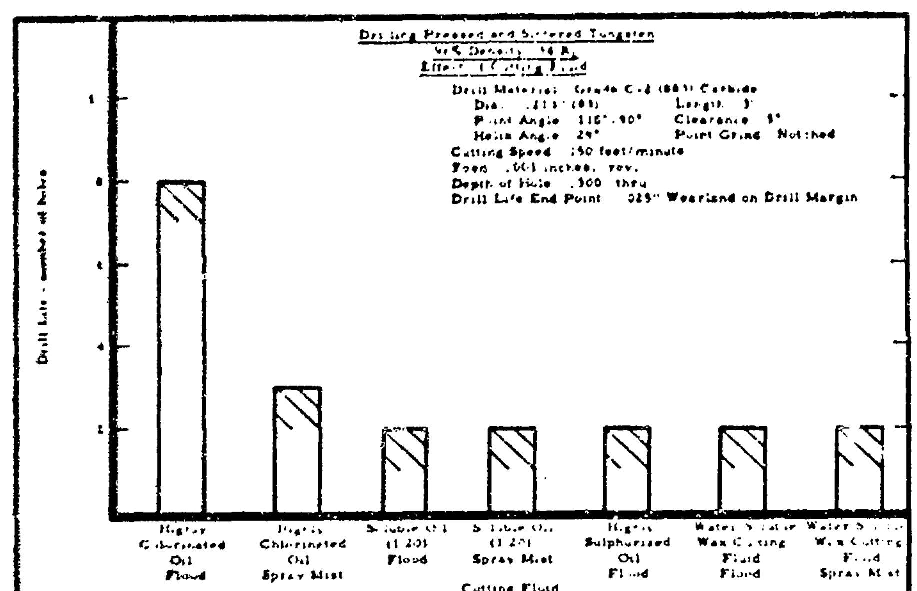
See Text, page 22

Figure



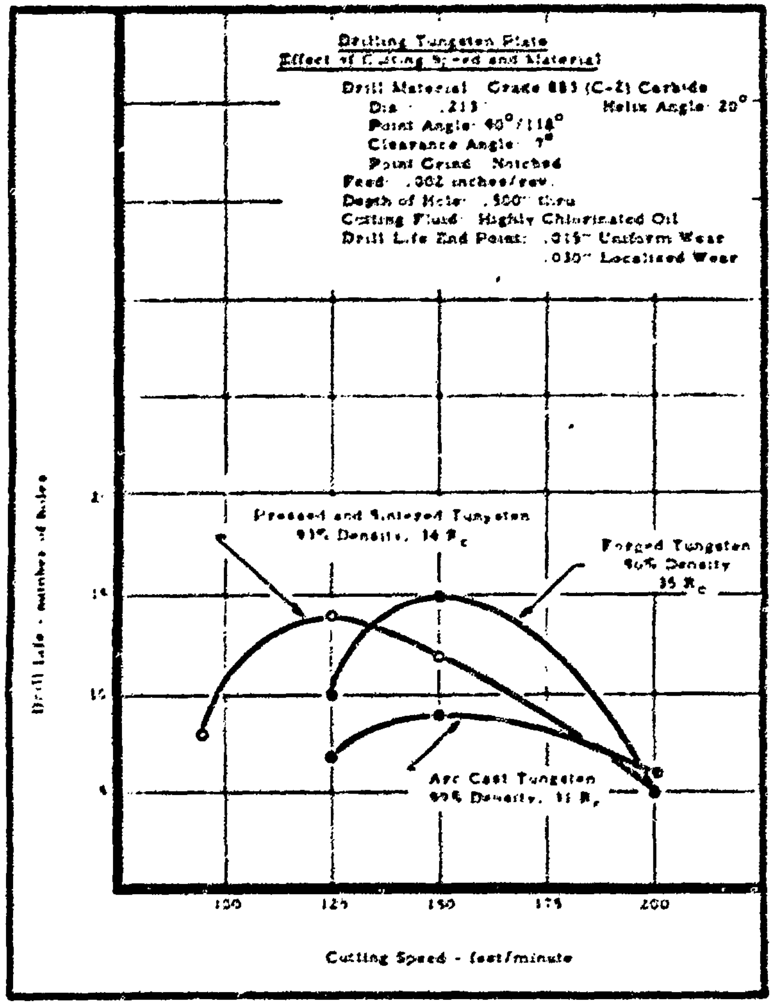
See Text page 22

Figure 17



See Text, page 22

Figure 18



See Text page 22

Figure 39

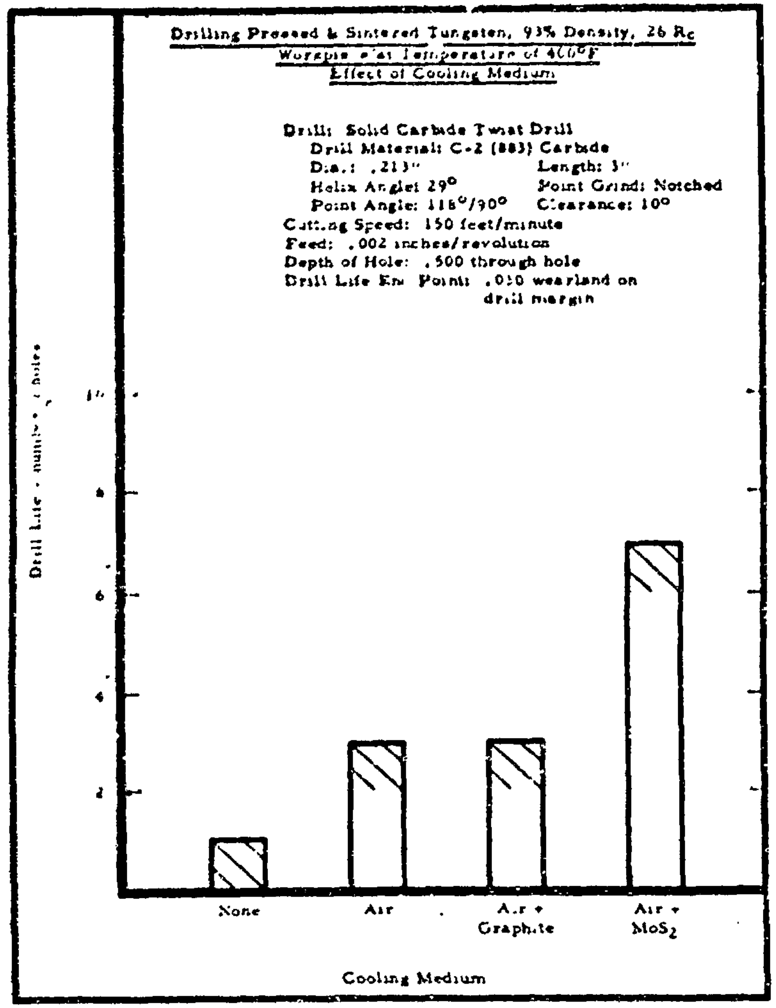


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Figure 40

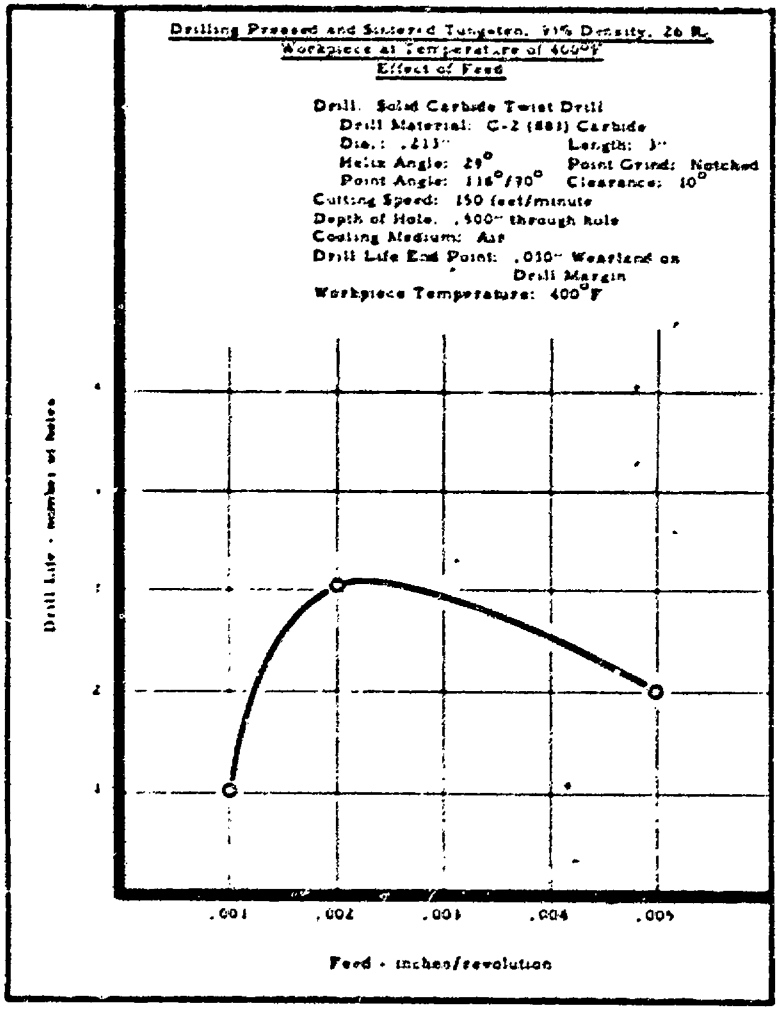

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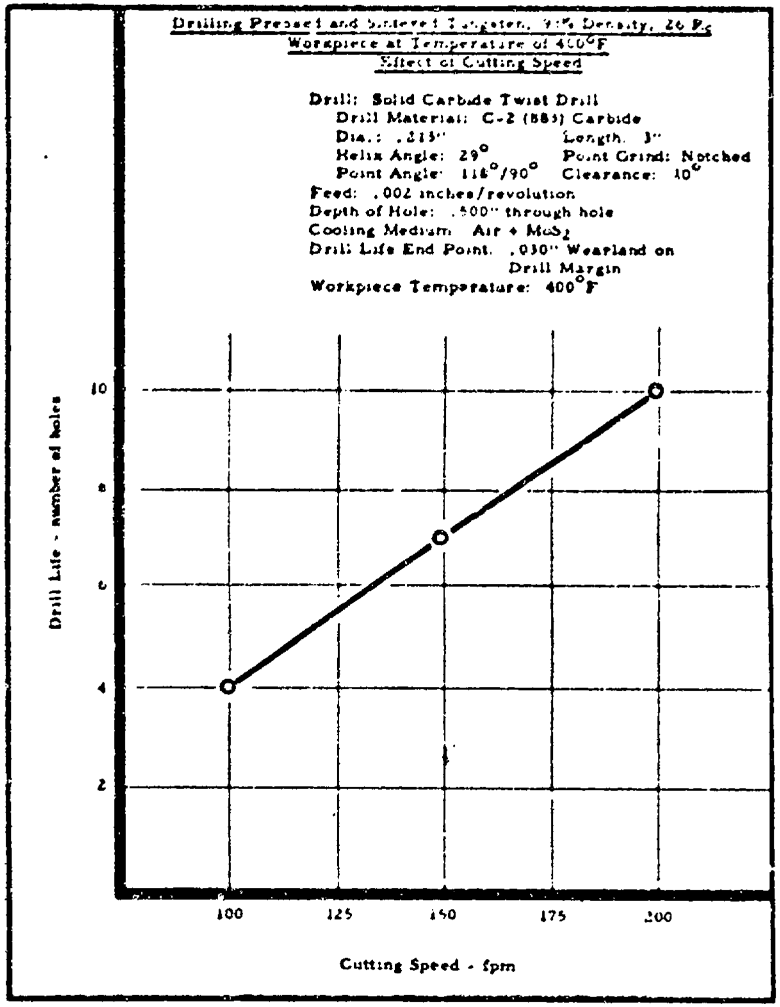
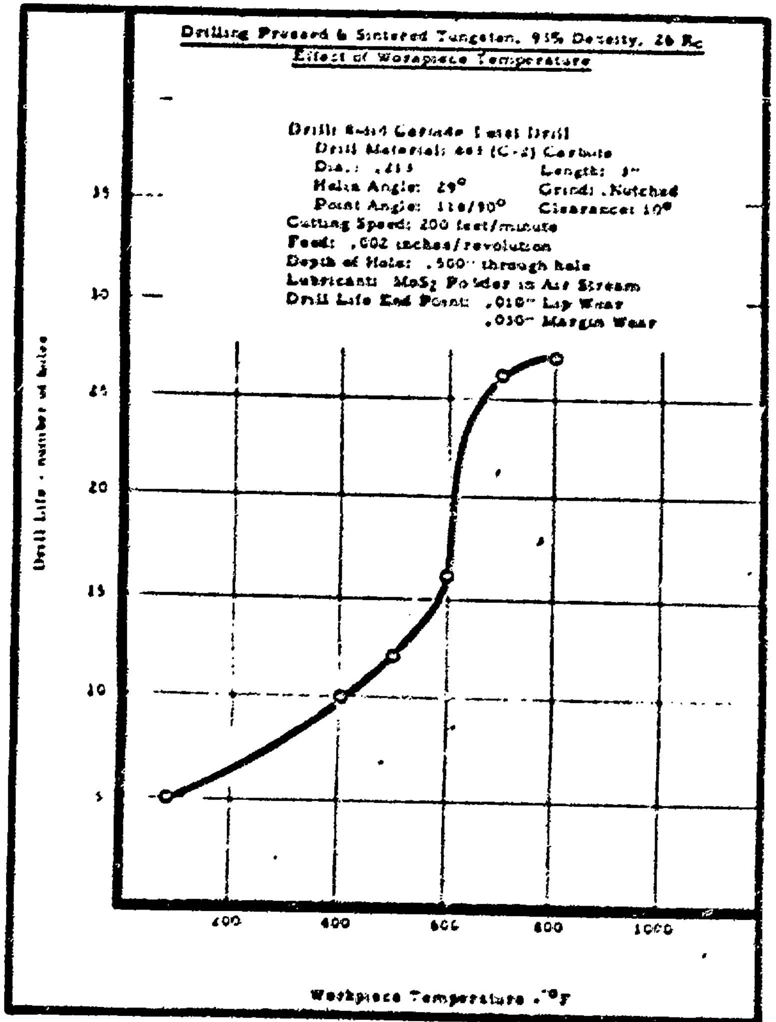
Figure 41



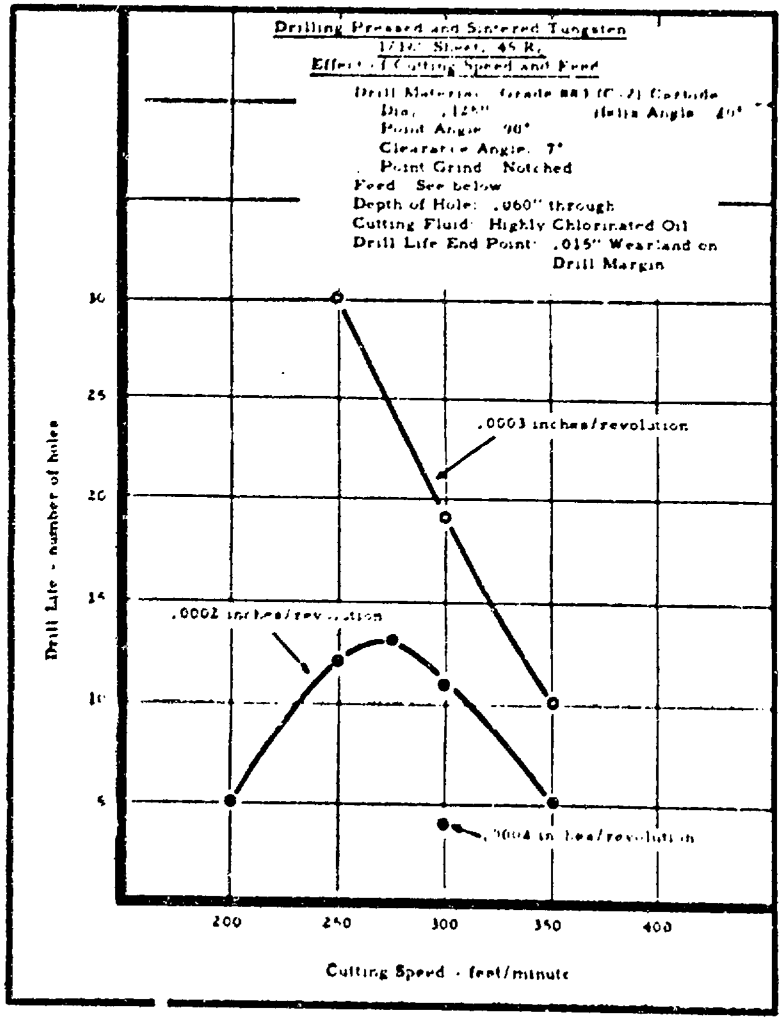
See Text, page 23

Figure 42



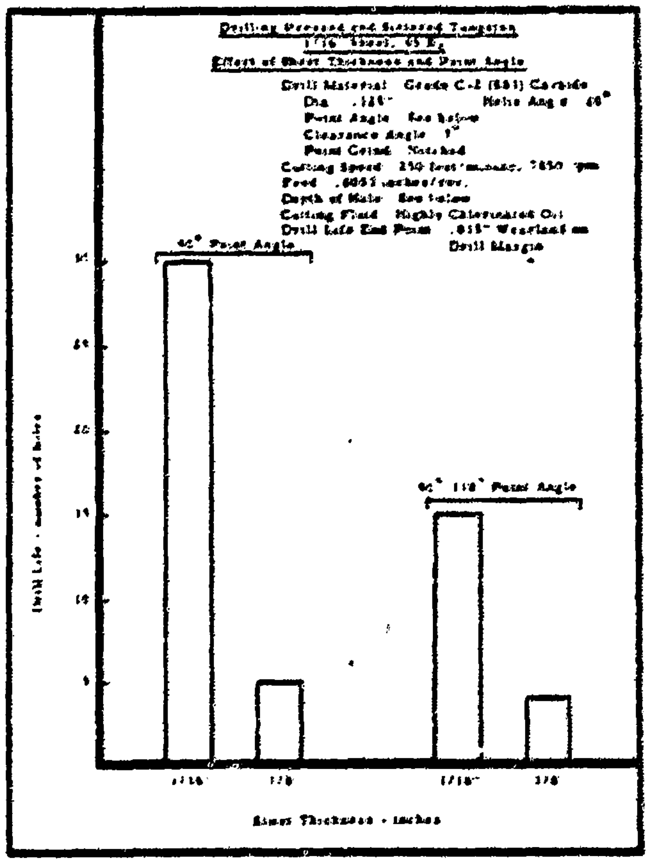
See text, page 43

Figure 43

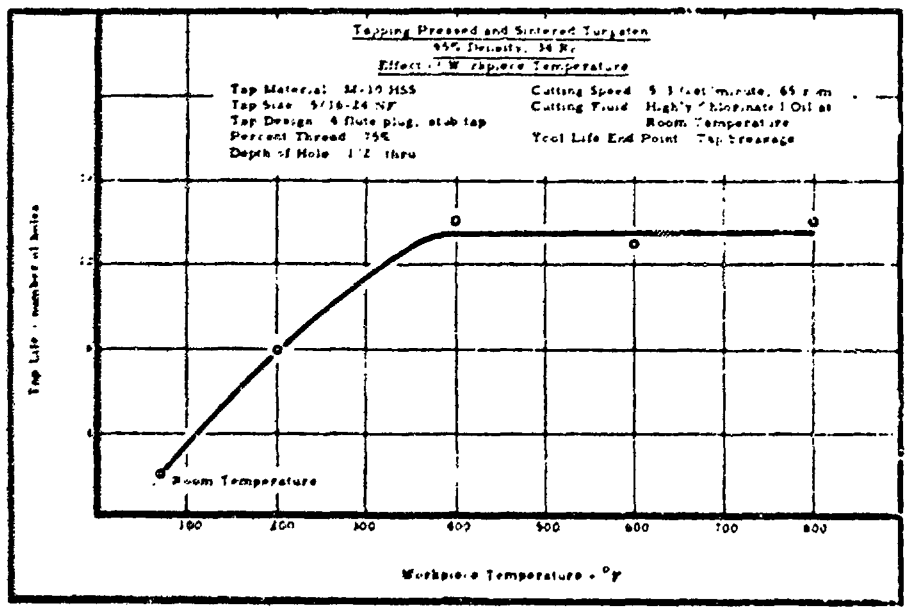


See Text, page 23

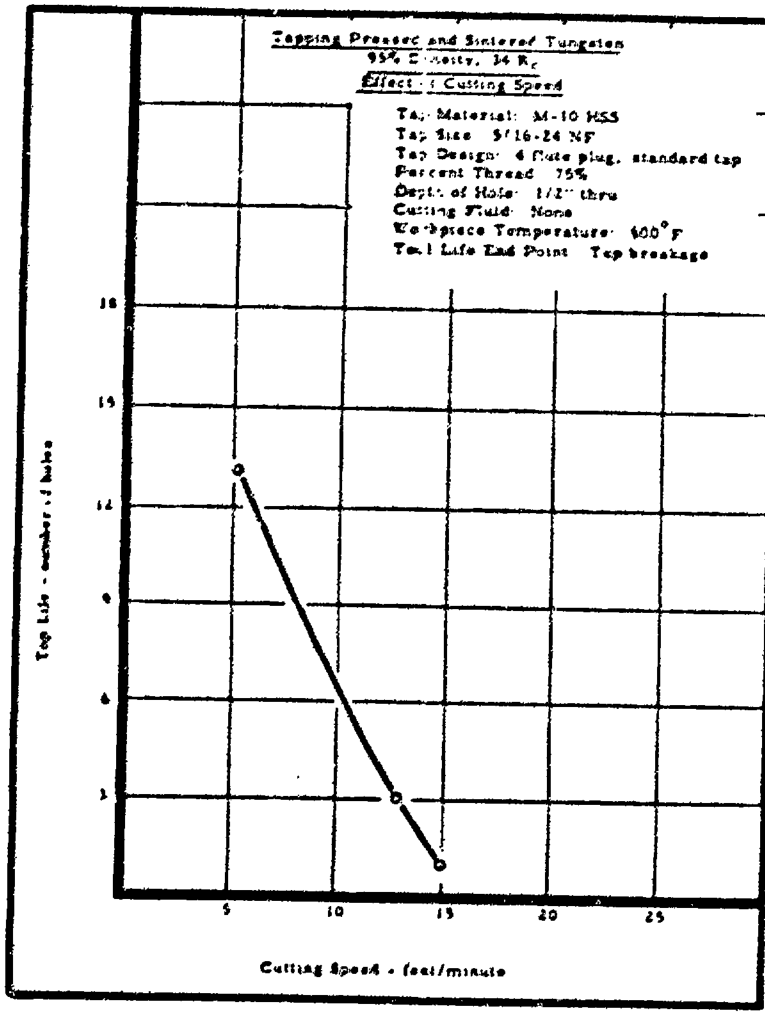
Figure 44



See Text page 43 Figure 45

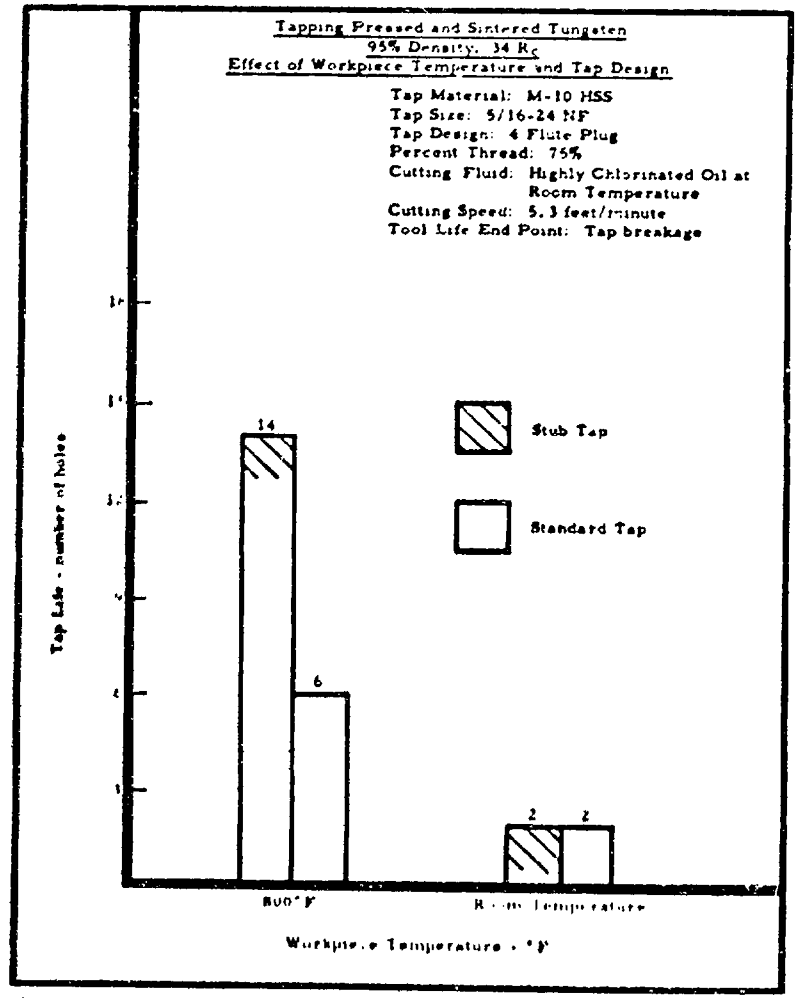


See Text, page 26 Figure 46



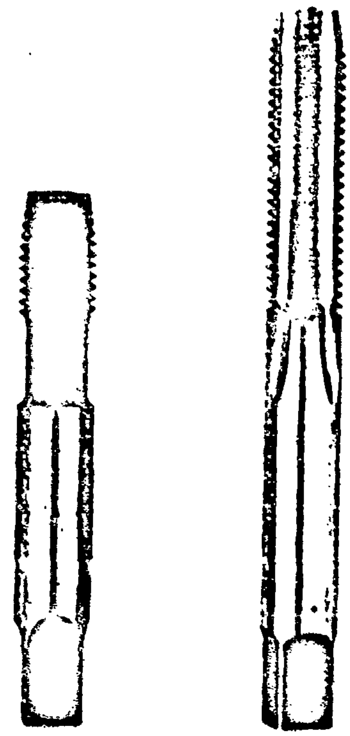
See Text page 24

Figure 47



See Text, page 24

Figure 48



Special stub length type M-10 HSS tap (2" long) and standard length type M-10 HSS tap (2-3/4" long) used in tapping pressed and sintered tungsten. The maximum depth of hole that can be tapped with the special stub length tap is 1/2".

Figure 49

See Text, page 24

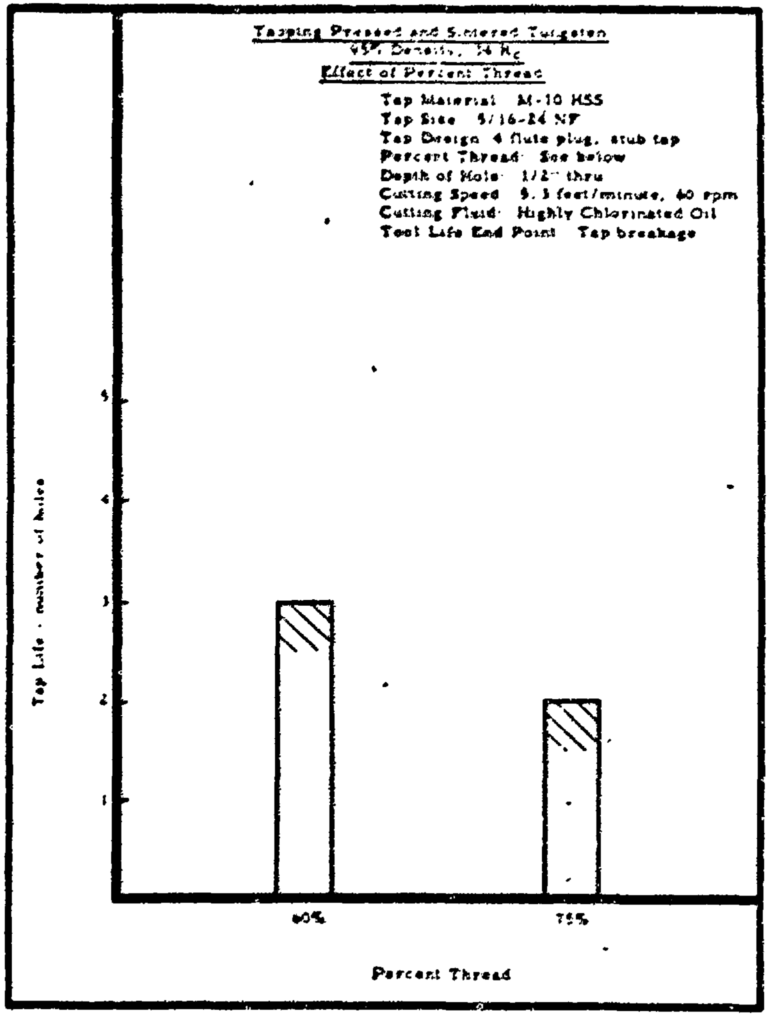


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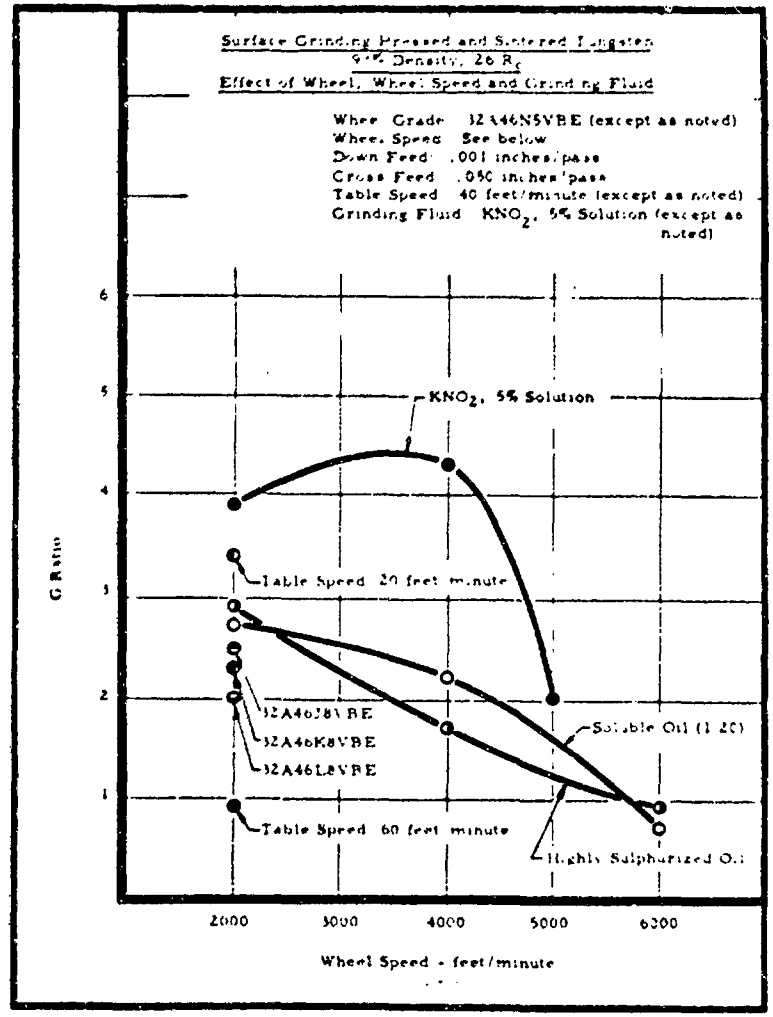
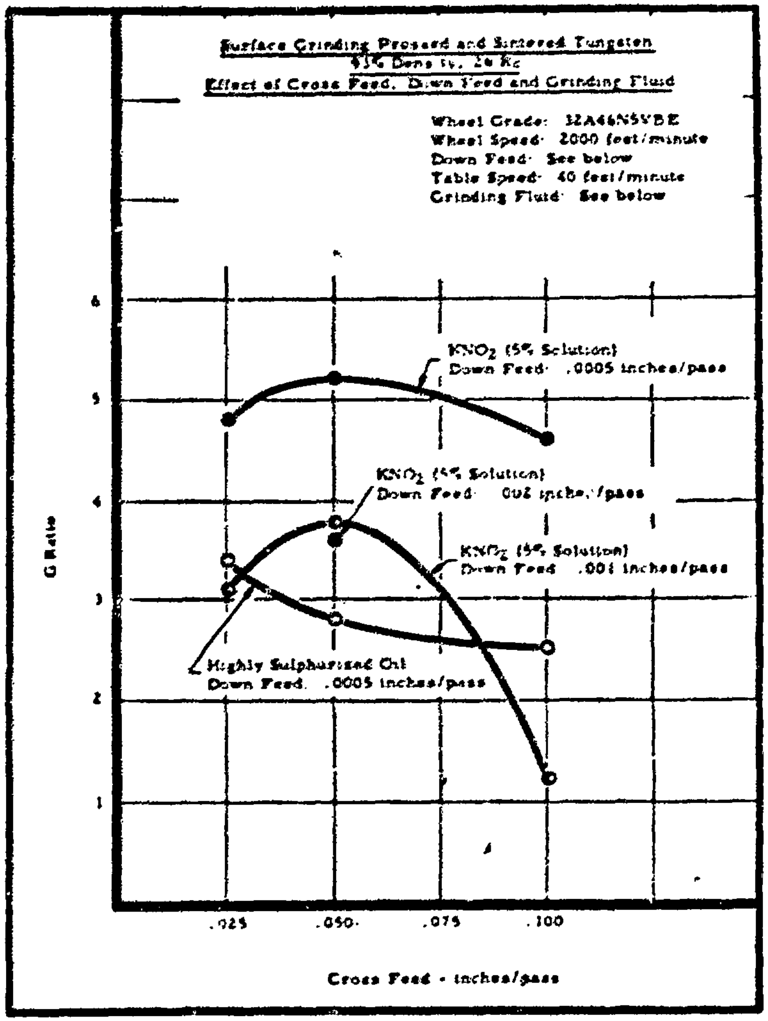
Figure 50



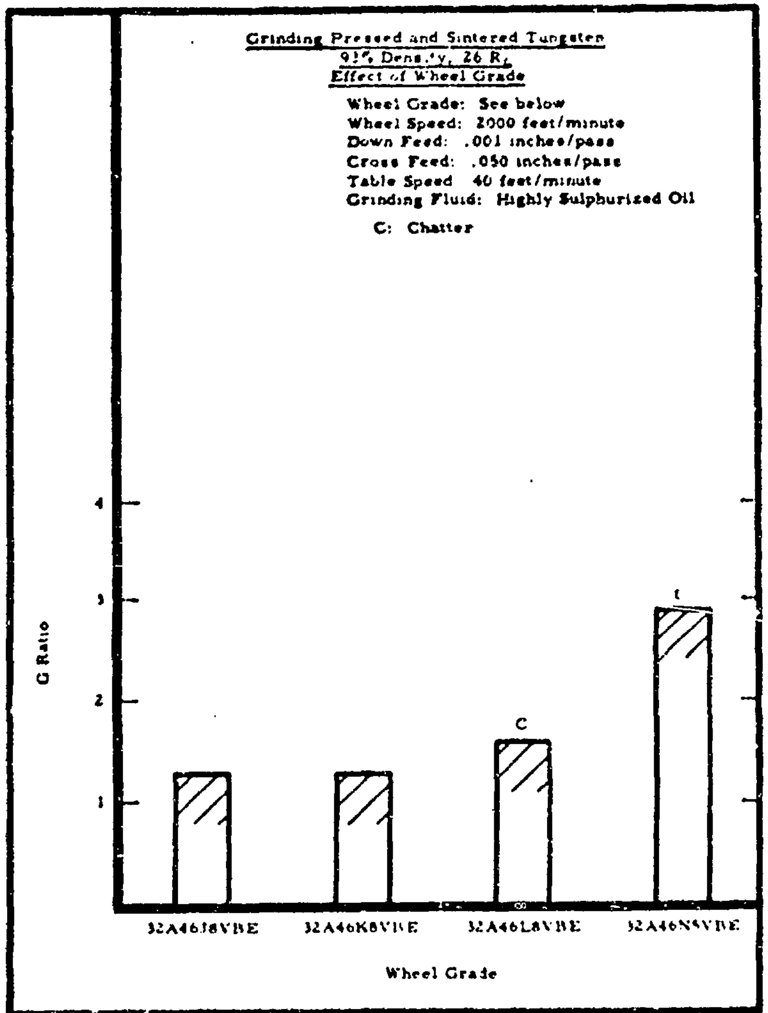
See text, page 25

Figure 51



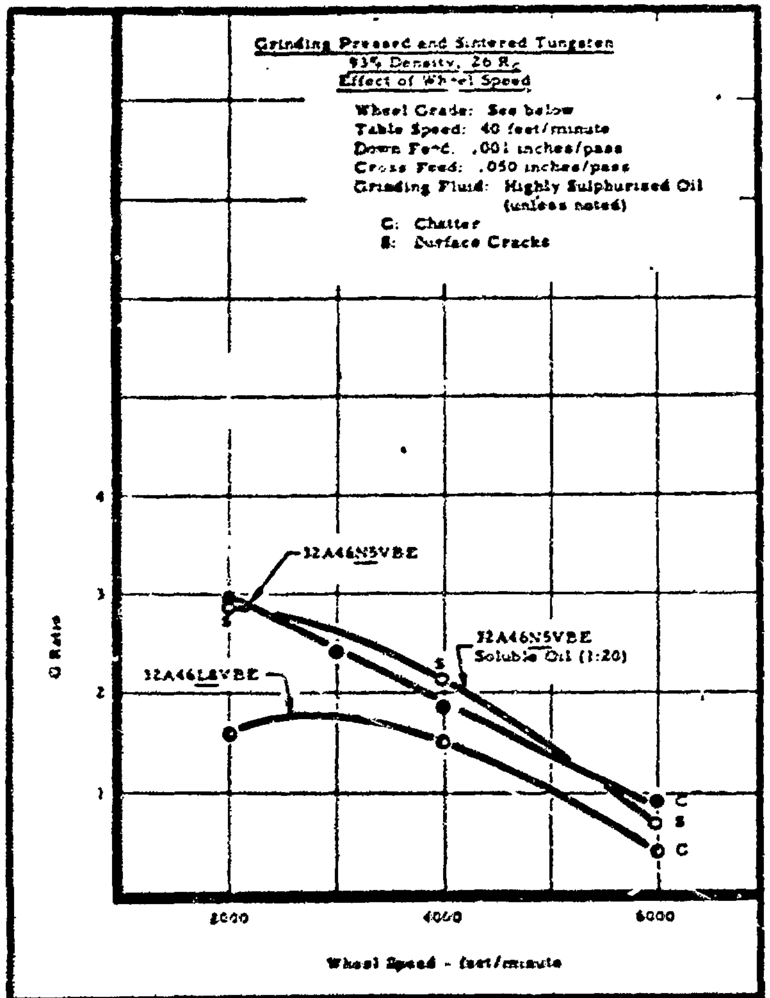
See text, page 25

Figure 52



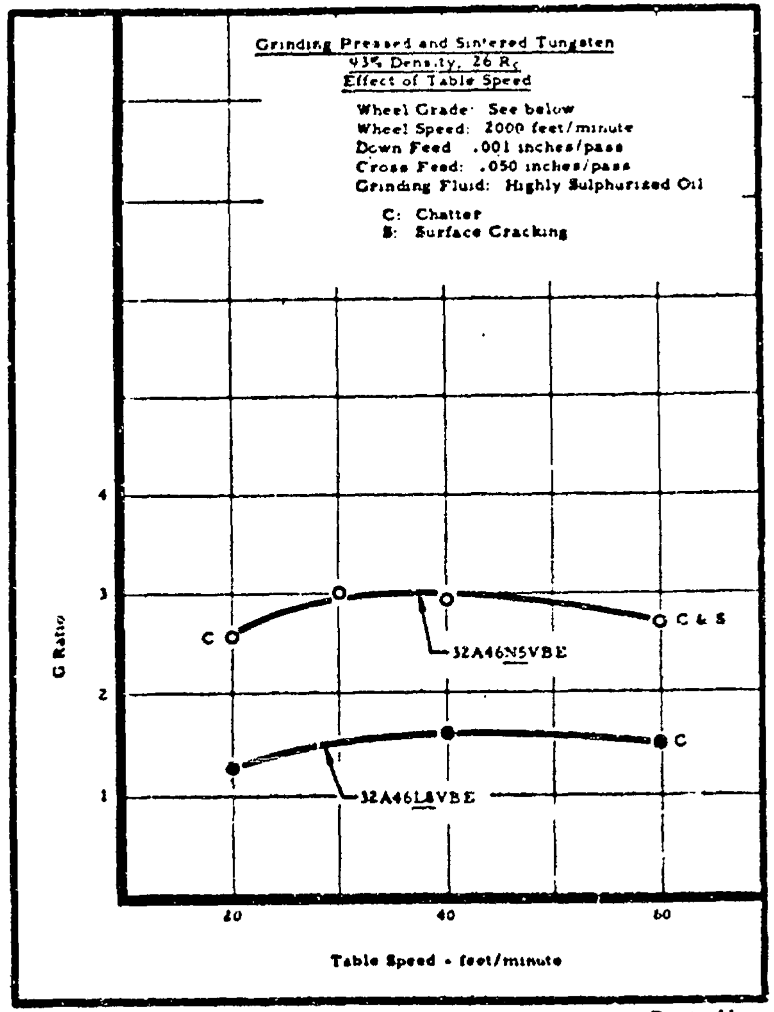
See Text, page 25

Figure 53



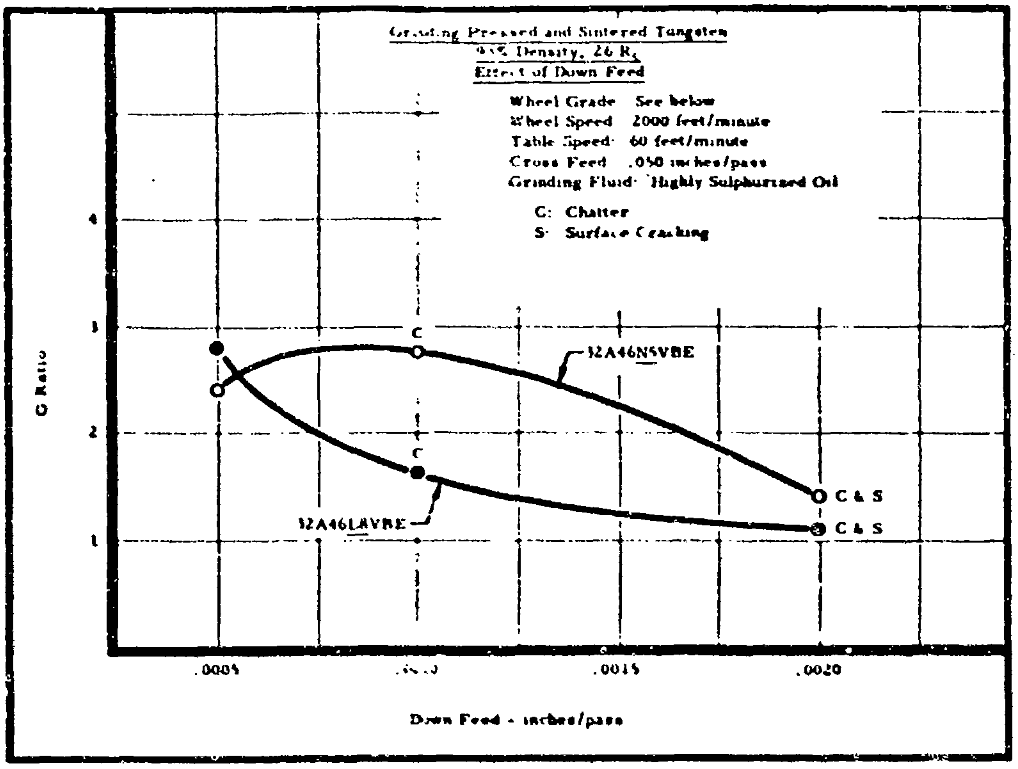
See Text, page 25

Figure 56



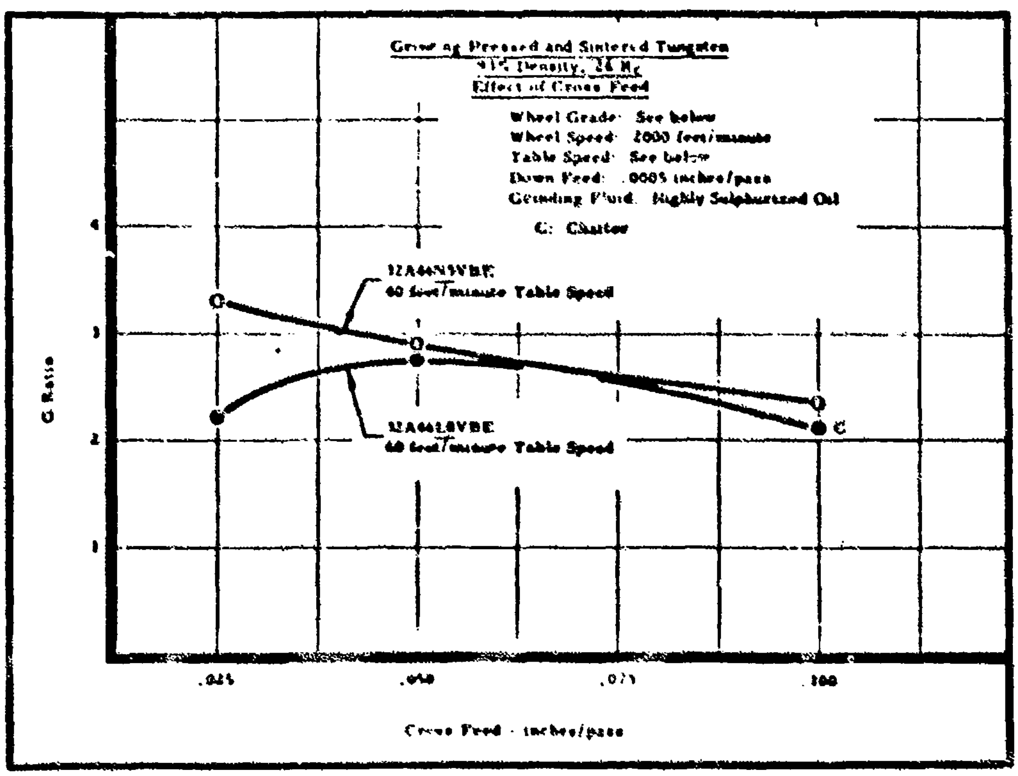
See Text, page 25

Figure 55



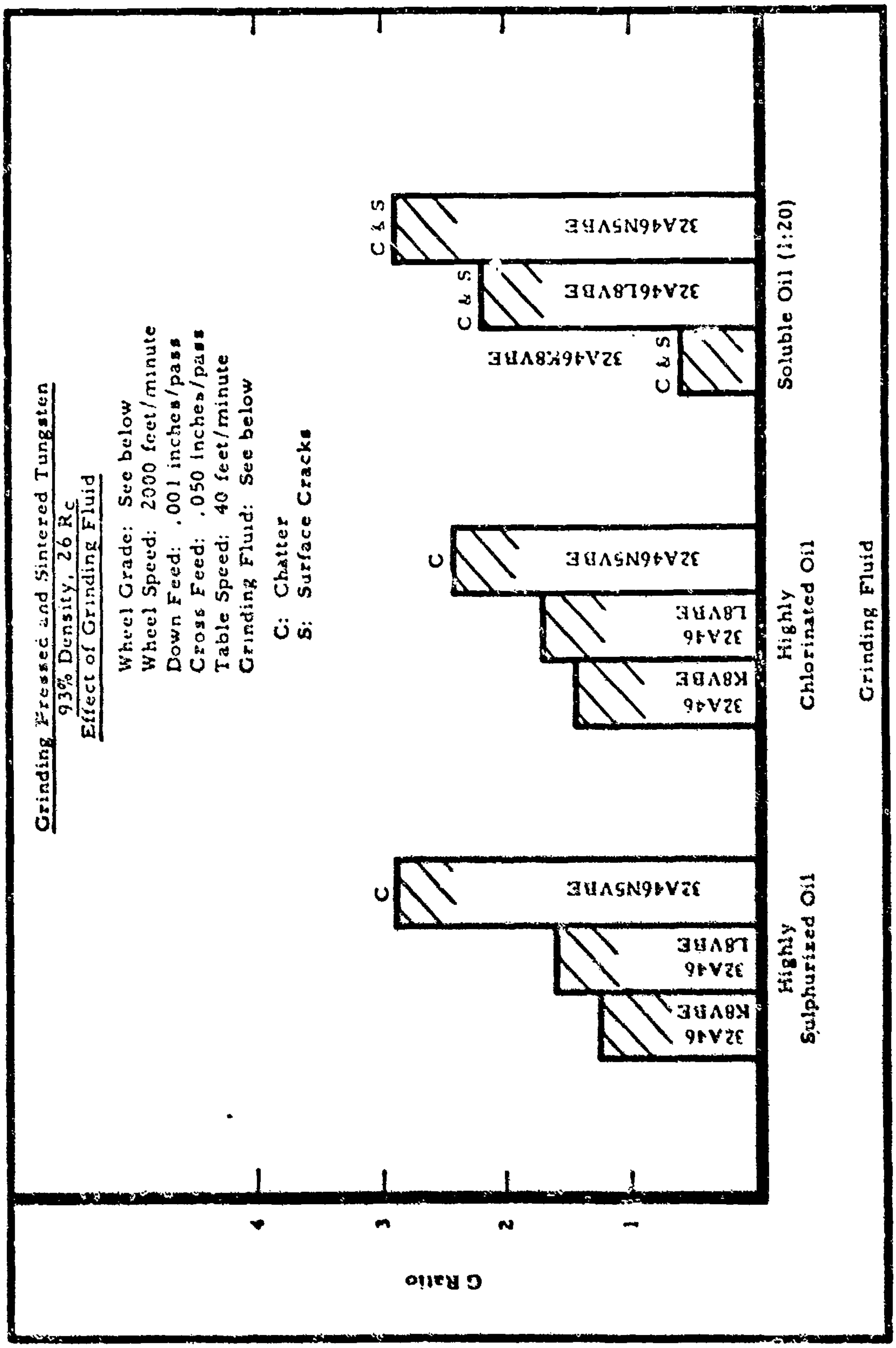
See Text, page 25

Figure 56



See Text, page 26

Figure 57



See Text, page 26

Figure 58

IV. MACHINING D-31 COLUMBIUM ALLOY

In the past few years, considerable effort has been expended in the development of columbium base alloys for structural applications in advanced aerospace vehicles and nuclear reactors. The advantages of columbium in these areas include its high melting point, low nuclear cross section and relative ease of fabrication. Columbium's advantageous tensile, creep and rupture strength in the range of 2000 to 2500°F make it a logical choice for many air frame and propulsion system components. Typical applications include skins and panels, engine mounts, supportings, and a variety of related attachments and fittings.

For machining tests, the alloy D-31 was selected as being representative of the group of columbium alloys presently available. This alloy was machined in the extruded and stress relieved condition. In addition to the machinability data presented on the D-31 alloy, a limited amount of surface grinding data is given on unalloyed columbium. Typical microstructures of the unalloyed and D-31 columbium alloy are shown in Figure 59, page 61. The nominal chemical composition is shown in Table 3.

Table 3
Chemical Composition of D-31 Columbium Alloy

Material	Nominal Composition, Percentage			Average Hardness
	Ti	Mo	Cb	BHN
D-31	10.0	10.0	Bal	207-217

Recommendations for Machining D-31 Columbium Alloy

D-31 columbium has proved to be one of the least difficult to machine refractory alloys investigated in this program. The machining characteristics of this alloy are very similar to the austenitic stainless steels. Since columbium is considerably more ductile than tungsten at room temperature, no work breakout or chipping was encountered when machining this alloy. Surface finish in machining, while not as good as obtained when machining the stainless steels, was generally acceptable. Most machining operations can be performed with high speed steel cutting tools; however, carbide tools will permit much higher production rates.

The data obtained in machining D-31 columbium alloy has been reviewed and the recommendations for machining this alloy are given in Table 4, pages 62 and 63.

Turning

Appreciable differences were found in the various carbide grades used in turning the D-31 columbium alloy. As shown in Figure 60, page 64, the C-6 grade was the poorest and the C-2 grade the best. The high cost of D-31 columbium, $120 per pound, did not permit the removal of a large volume of metal for a given tool life. A .030" depth of cut was selected for the tests as representative of semi-finishing cuts. A comparison of the C-2 grade of carbide with high speed steel and cast alloy tools is presented in Figure 61, page 64. The cutting speed with carbide was 50% faster than with the cast alloy and more than 300% faster than with high speed steel tools for equivalent tool life.

When turning with M-2 high speed steel tool, the tool life decreased rapidly when the feed was increased above .005 in./rev. The tool life curve versus feed in Figure 62, page 65, indicates that the tool life at a feed of .009 in./rev. was only one-third the tool life obtained at a feed of .005 in./rev.

Tool geometry is also a very important factor in turning the D-31 columbium alloy with high speed steel tools. Note in Figure 63, page 65, how the tool life increased when the side rake angle was increased. Changing the side rake from 20° to 30° more than doubled the tool life.

Face Milling

The relationship between tool life and cutting speed is shown in Figure 64, page 66, for a feed of .010 in./tooth with an M-2 high speed steel face milling cutter. In addition, test points are presented for lighter and heavier feeds. At a feed of .010 in./tooth, the best tool life was obtained at a cutting speed of 100 feet per minute. Test data in the chart also indicates that by reducing the feed 50% to .005 in./tooth, tool life was doubled. Tool life was improved considerably by using premium grades of high speed steel tools as shown in Figure 65, page 66.

A further increase in tool life was obtained through the use of a highly chlorinated oil, see Figure 66, page 67. As shown in Figure 67, page 67, tool geometry is another important factor in milling the D-31 columbium alloy with high speed steel tools. An axial rake of 0° and a radial rake of 30° proved best.

A comparison of the tool life curves in Figures 64 through 68, pages 66 through 68, shows that the cutting speed with carbide was 40% higher than with an M-2 high speed steel cutter. The feed was .010 in./tooth in both cases.

End Milling

The proper selection of cutting fluid in end milling the D-31 columbium alloy is very important. Note in Figure 69, page 68, the great differences obtained in tool life with the three cutting fluids tested. The highly chlorinated oil was considerably better than the soluble oil and slightly better than the highly sulphurized oil.

End Milling (continued)

The tool life curves in Figure 70, page 69, demonstrate the advantage of the T-15 high speed steel cutter over the M-2 cutter. The cutting speed for the equivalent tool life was 35% higher with the T-15 than with the M-2 cutter.

As shown in Figure 71, page 69, the feed is also very critical. Tool life at a feed of .002 in./tooth was over 200 inches of work travel, while at a feed of .001 in./tooth about 120 inches of work travel was obtained and when a feed of .003 in./tooth was used, the tool life was nil.

Drilling

The effect of cutting speed and feed in drilling the D-31 columbium alloy is demonstrated in Figure 72, page 70. A feed of .002 in./rev. permitted a 50% increase in cutting speed over that permitted with a feed of .005 in./rev. for equivalent drill life. However, the production rate on the 85 holes drilled at 75 feet/minute using a .005 in./rev. feed was greater than that for the 85 holes drilled at 120 feet/minute and the .002 in./rev. feed. A tool life curve for a range of cutting speeds is shown in Figure 73, page 70, for a 1/8" diameter drill at a feed of .005 in./rev.

In the smaller size drills, feed is even more important. Note in Figure 74, page 71, the abrupt decrease in drill life when the feed was increased with a 1/16" diameter drill. Also note how drill life improved when the cutting speed was increased from 25 to 50 feet/minute. Chip removal was more efficient at the higher drilling speed. A feed of .0005 in./rev. at a cutting speed of 50 feet/minute is recommended on drills .062" in diameter. These drilling conditions provide a drill penetration rate of 1.5 in./min.

Another important factor in drilling small diameter holes is the length of the drill. In the chart in Figure 75, page 71, the overall length of the drill was 1-5/8"; however, by reducing the drill length from 1-5/8" to 1-1/4", the drill life increased from 15 holes to 61 holes.

Reaming

In reaming, the hole size was periodically checked with a plug gage. All of the tests reported were discontinued when a wearland of .012" was observed on the reamer cutting edges. At this point, the change in hole size was under .001".

The relationship between cutting speed and reamer life is illustrated in Figure 76, page 72. Using a 10° right hand spiral reamer and a highly sulphurized oil, 100 holes .213" diameter, can be reamed at a cutting speed of 125 feet/minute. The reamer life was appreciably less with either the highly chlorinated or the soluble oil. As indicated by Figure 77, page 72, the feed rate is extremely important. A very significant reduction in reamer life resulted when the feed was reduced

Reaming (continued)

from .005 in./rev. to .002 in./rev. An even greater reduction occurred when the feed was increased to .009 in./rev.

Tapping

A relatively low cutting speed must be used in tapping the D-31 columbium alloy. Note in Figure 78, page 73, that at a cutting speed of 12 feet/minute, 50 holes were tapped, while only 17 holes were tapped at 16 feet/minute. The selection of cutting fluid is also critical. The chart in Figure 79, page 73, demonstrates the superiority of the highly chlorinated oil over various other types.

Grinding

Grinding wheel wear is very rapid in grinding D-31 columbium. However, this alloy is not prone to developing surface cracks provided moderate grinding conditions are employed. The grinding wheel becomes loaded very rapidly. Wheels must be dressed often and flooded liberally with a grinding fluid. Surface finishes of the order of 10 to 50 microinches were obtained in the tests reported.

The bar charts in Figures 80 and 81, page 74, indicate that the best wheel of the group tested was the grade 32A46K8VBE for the surface grinding of both the unalloyed columbium and the D-31 columbium alloy. Various grinding fluids are also compared in Figure 82, page 75, on both metals. Note that potassium nitrite (KNO_2) was the best of the group on the D-31 columbium alloy.

The relationship between wheel speed and G ratio is presented in Figure 83, page 75. Note how rapidly the G ratio decreased on the D-31 columbium alloy when the wheel speed was increased beyond 4000 feet/minute.

The effect of table speed on G ratio is shown in Figure 84, page 76, for two types of wheels. As shown in the chart, a change in table speed over a range of 20 to 60 feet/minute did not appreciably affect the grinding ratio. However, as illustrated in Figures 85 and 86, pages 76 and 77, increasing either or both the down feed or the cross feed can adversely affect the G ratio.

Three sets of grinding conditions are given in the table of recommended machining conditions for D-31 columbium. The first set of conditions employ a low wheel speed and down feed to obtain the highest G ratio possible, 7.5. The second condition uses a higher wheel speed and down feed with a nitrite grinding fluid. The grinding ratio obtained is 4.5 in this case. The use of potassium nitrite as a grinding fluid is sometimes considered objectionable because of the difficulty in keeping the machine clean, and the tendency of the salt deposits to gum up moving parts. A third set of conditions given recommend a conventional soluble oil for the grinding fluid, but the grinding ratio is reduced to 3.5 when this fluid is used.

D-10 Unalloyed Columbium
Extruded and Stress Relieved, 112 BHN
Microstructure consists of equiaxed, single phase grains.
Magnification: 500X   Etchant: 20 ml. HNO_3
4 ml. HF
40 ml. H_2O

D-31 Columbium Alloy
Extruded and Stress Relieved, 217 BHN
Microstructure consists of columbium alloy matrix plus bonds of precipitates.
Magnification: 500X   Etchant: 20 ml. HNO_3
4 ml. HF
40 ml. H_2O

Figure 59

See Text, page 57

TABLE 4
RECOMMENDED CONDITIONS FOR MACHINING AND GRINDING
D-31 COLUMBIUM ALLOY, 207 BHN

Nominal Chemical Composition, Percent

Ti	Mo	Cb
10.0	10.0	Bal.

Operation	Tool Material	Tool Geometry	Tool Used for Tests	Depth of Cut inches	Width of Cut inches	Feed	Cutting Speed ft./min	Tool Life	Wear-land inches	Cutting Fluid
Turning	M-2 HSS	BR: 0° SCEA: 0° SR: 20° ECEA: 5° Relief: 5° NR: 1/64"	5/8" square solid HSS	.030	---	.005 in/rev	60	40+ min.	.030	Soluble Oil (1:20)
Turning	C-2 Carbide	BR: 0° SCEA: 0° SR: 20° ECEA: 5° Relief: 5° NR: 1/64"	5/8" square brazed tool bit	.030	---	.005 in/rev	300	40+ min.	.010	Soluble Oil (1:20)
Face Milling	Super HSS	AR: 0° ECEA: 5° RR: 20° CA: 45° Clearance: 10°	4" diameter single tooth face mill	.030	1-1/2	.010 in/tooth	135	50+ in/tooth	.016	Highly Chlorinated Oil
Face Milling	C-2 Carbide	AR: 0° ECEA: 10° RR: 10° CA: 45° Clearance: 10°	4" diameter single tooth face mill	.030	2	.010 in/tooth	150	90 in/tooth	.016	Highly Chlorinated Oil
End Mill Slotting	T-15 HSS	Helix Angle: 30° RR: 10° Clearance: 10° CA: 45°	1/2" diameter 4 tooth HSS end mill	.060	.500	.003 in/tooth	100	200+ inches	.008	Highly Chlorinated Oil
Drilling	M-1 HSS	118° plain point 7° clearance	.125" diameter drill 1-7/8" long	1/8" thru hole	---	.005 in/rev	75	175+ holes	.008	Highly Chlorinated Oil

See Text, page 57

TABLE 4 (continued)
RECOMMENDED CONDITIONS FOR MACHINING AND GRINDING
D-31 COLUMBIUM ALLOY, 207 BHN

Operation	Tool Material	Tool Geometry	Tool Used for Tests	Depth of Cut inches	Width of Cut inches	Feed	Cutting Speed ft./min	Tool Life	Wear-land inches	Cutting Fluid
Reaming	M-2 HSS	10° RH Helix CA: 45° Clearance: 10°	.213" diameter 6 flute chucking reamer	1/2" thru hole	.010" depth on hole radius	.005 in/rev	125	105 holes	.012	Highly Sulphurized Oil
Tapping	M-10 HSS	2 flute chip driver tap 75% thread	1/4-28 NF tap	1/2" thru hole	---	---	12	50 holes	---	Highly Chlorinated Oil

SURFACE GRINDING

Wheel Grade	Grinding Fluid	Wheel Speed feet/minute	Table Speed feet/minute	Down Feed inches/pass	Cross Feed inches/pass	G Ratio
32A46K8VBE	5% KNO_2 Solution	2000*	40	.0005	.025	7.5
32A46K8VBE	5% KNO_2 Solution	4000	40	.001	.050	4.5
32A46K8VBE	Soluble Oil (1:20)	4000	40	.001	.050	3.5

* If wheel speed of 2000 feet/minute is not available, use conditions for wheel speed of 4000 feet/minute.

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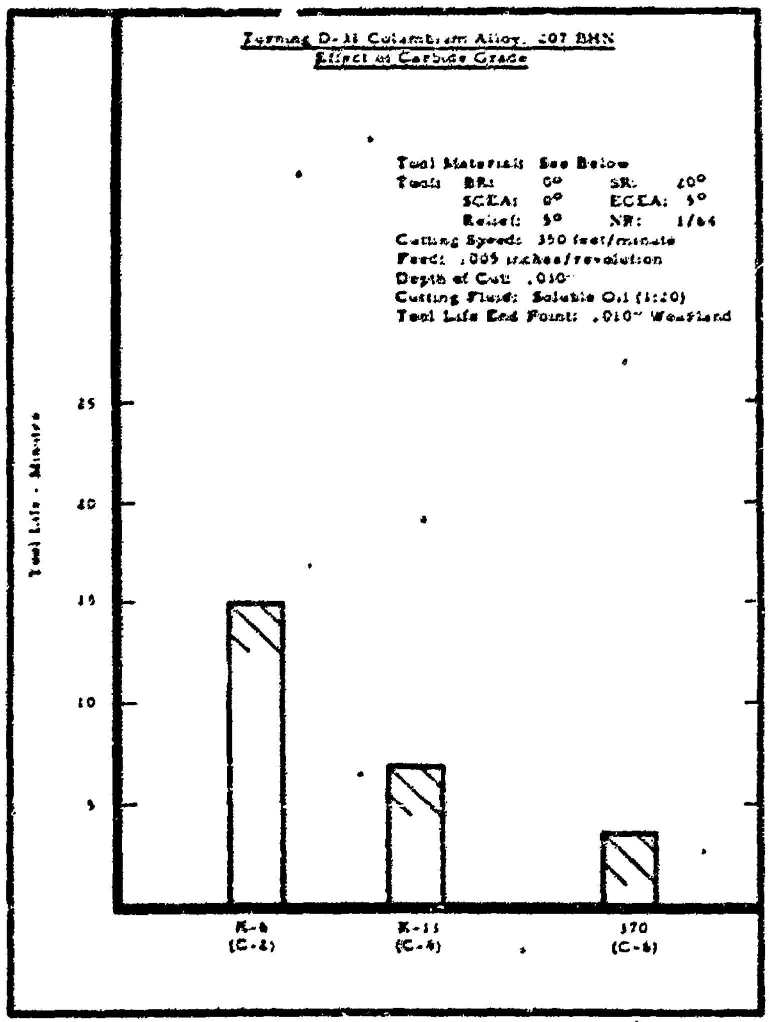
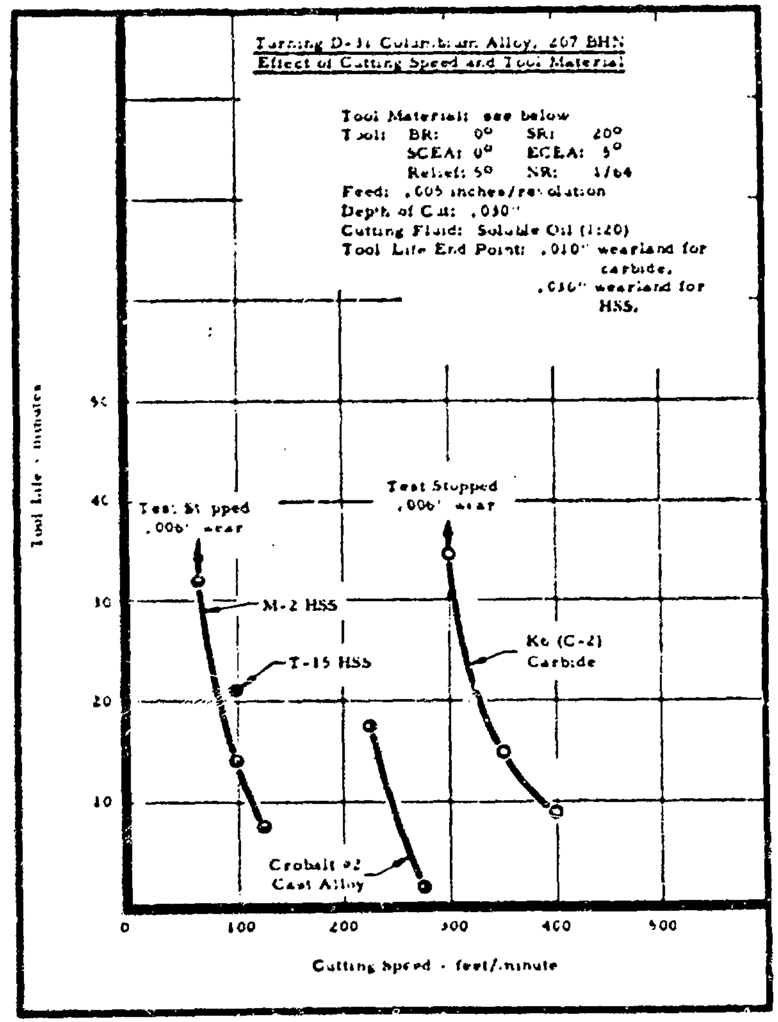


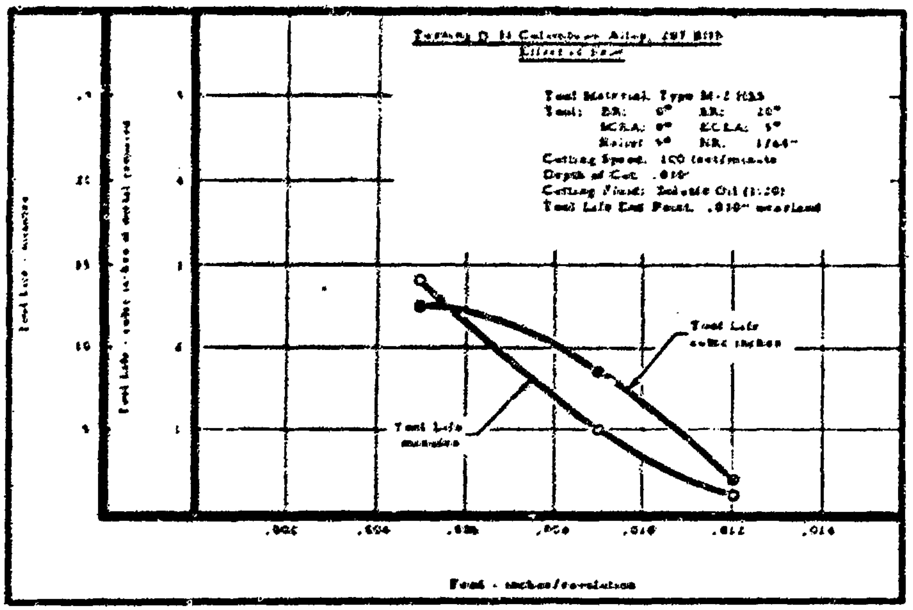
See text, page 58

Figure 60



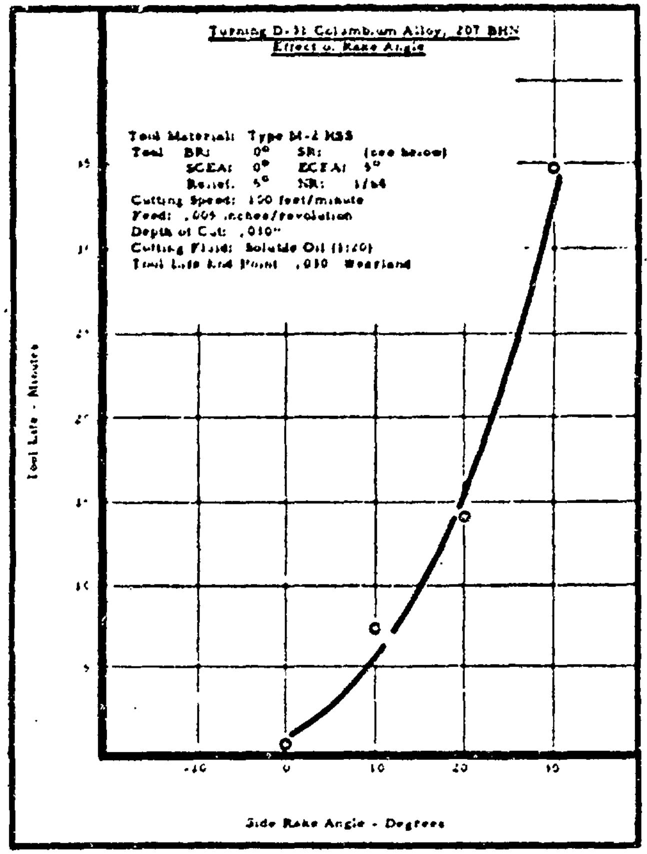
See text, page 58

Figure 61



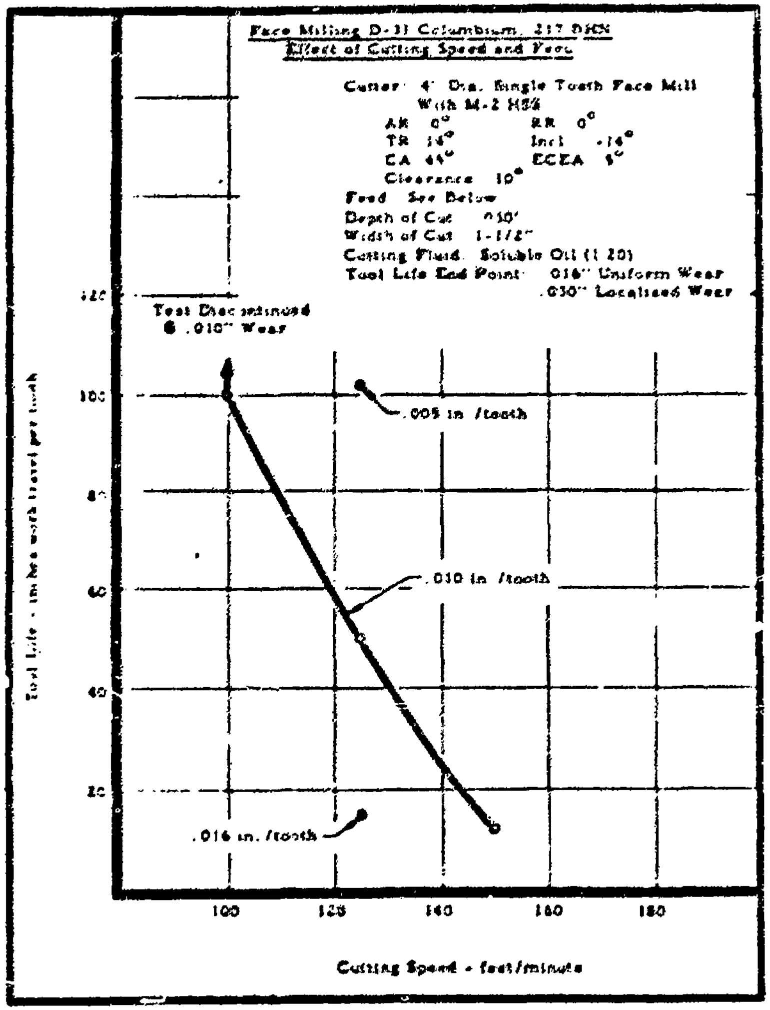
See Text, page 58

Figure 62



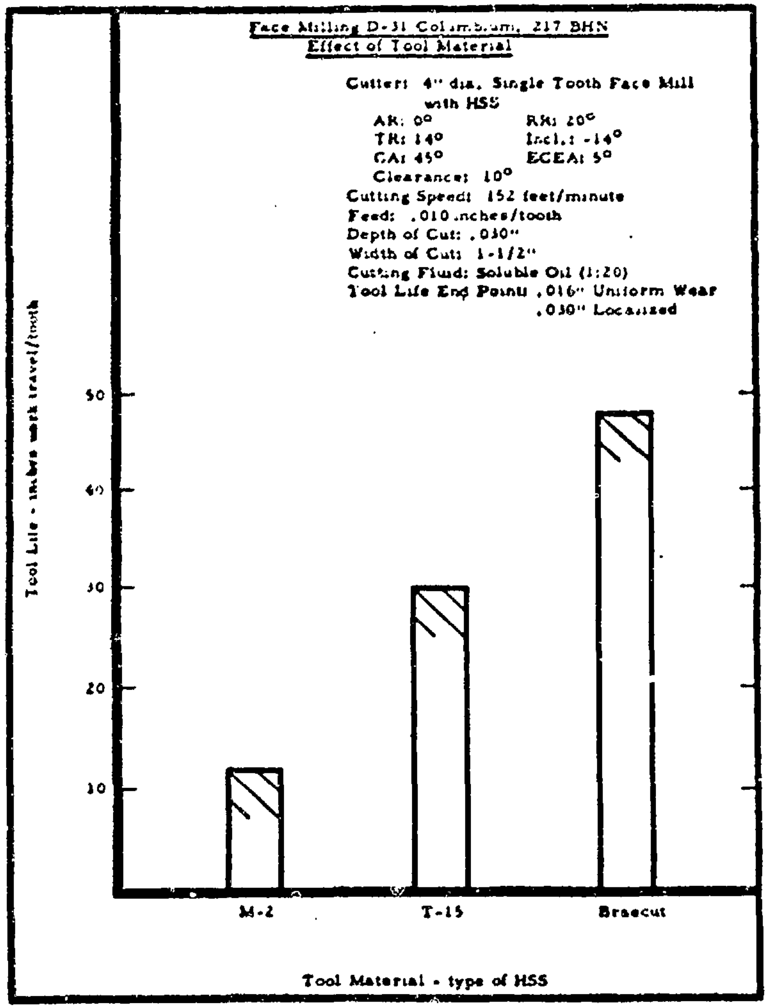
See text, page 58

Figure 61



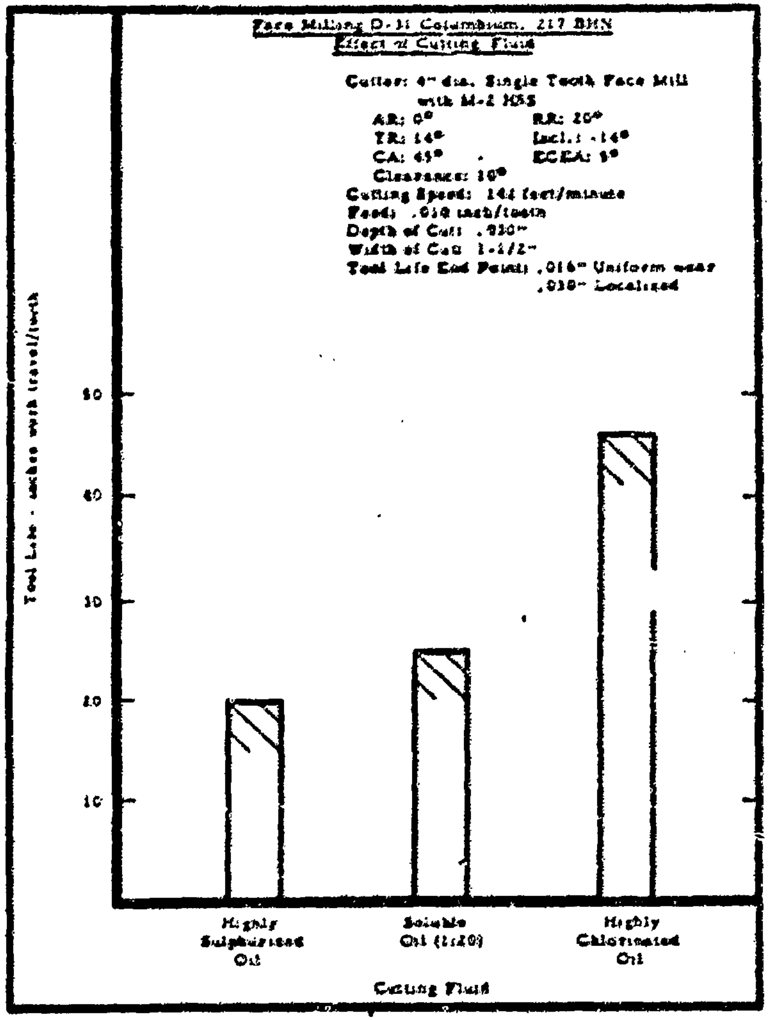
See Text page 58

Figure 64



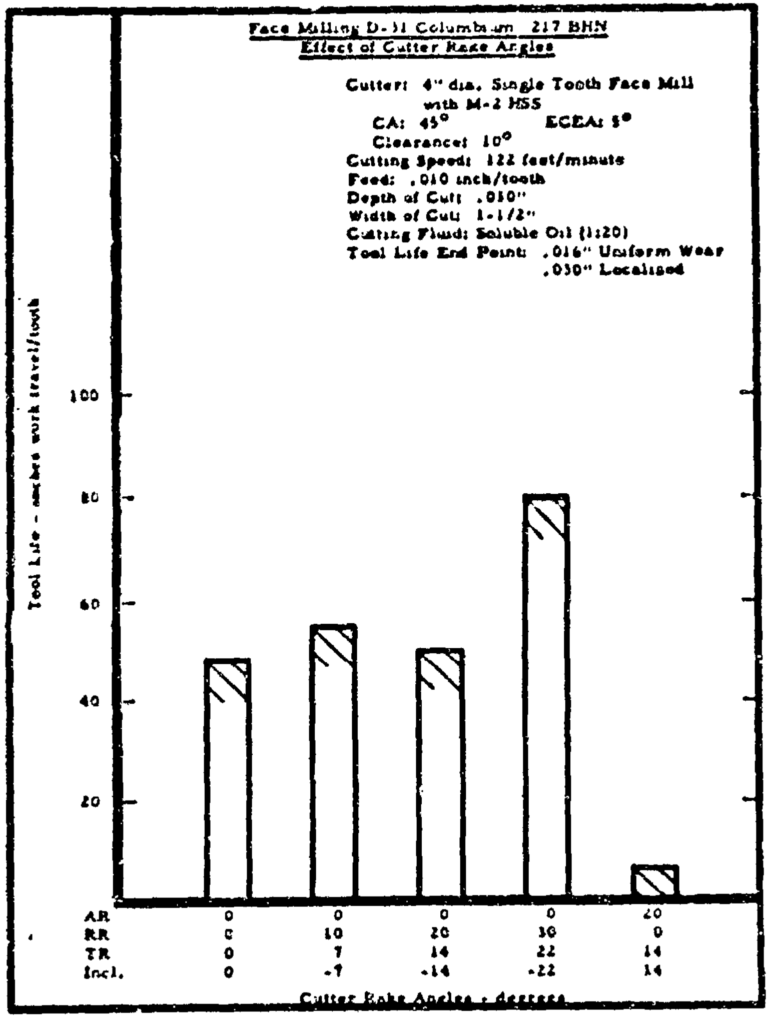
See text, page 58

Figure 65



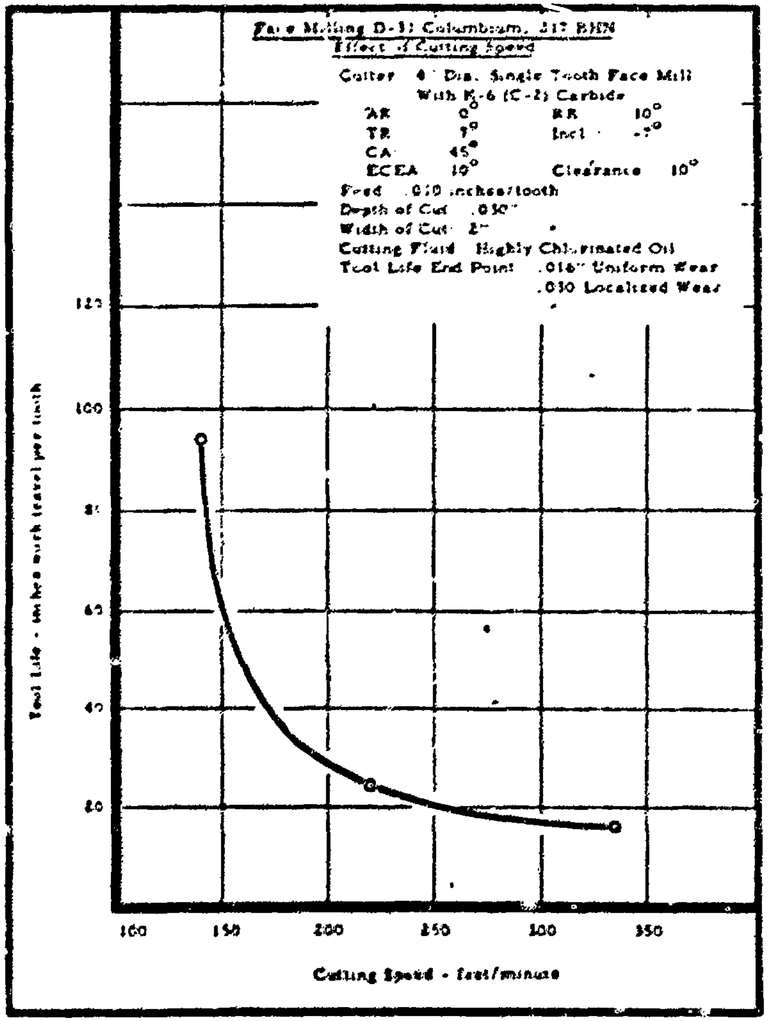
See text, page 58

Figure 66



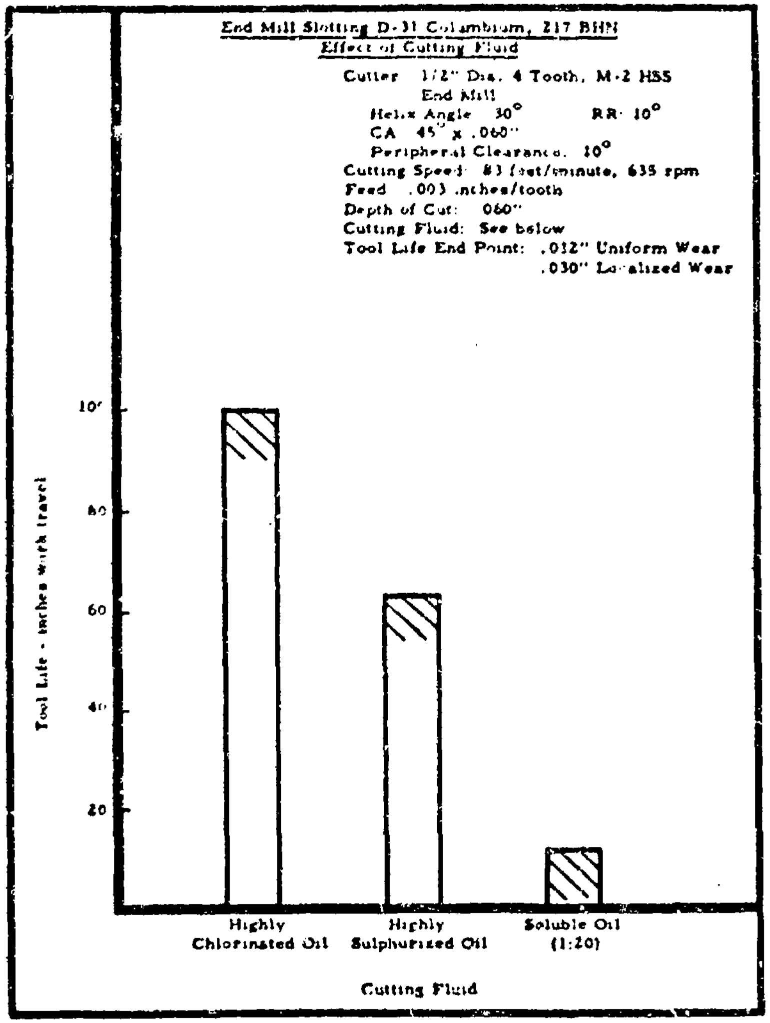
See text, page 58

Figure 67



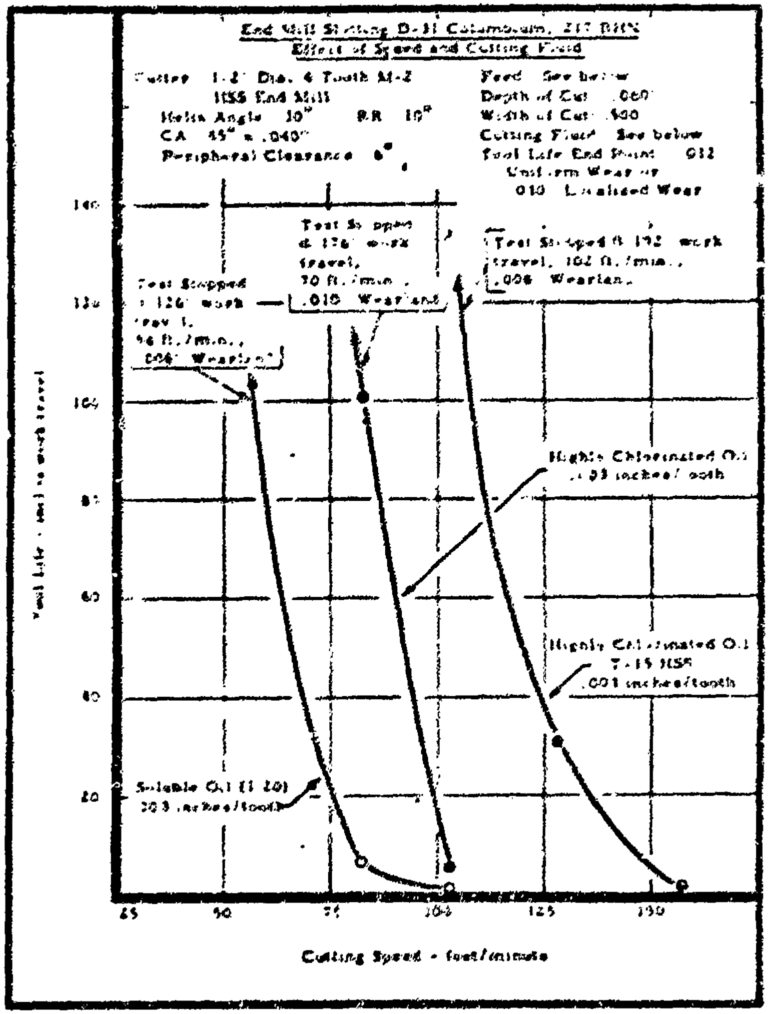
See Text page 58

Figure 68



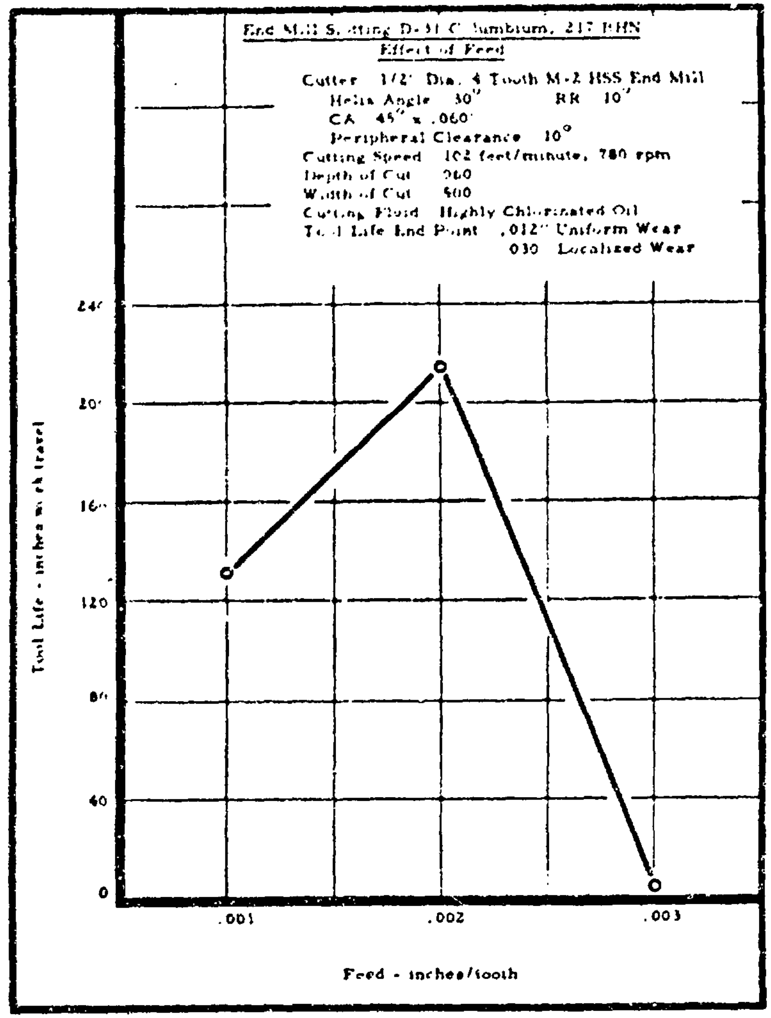
See Text page 58

Figure 69



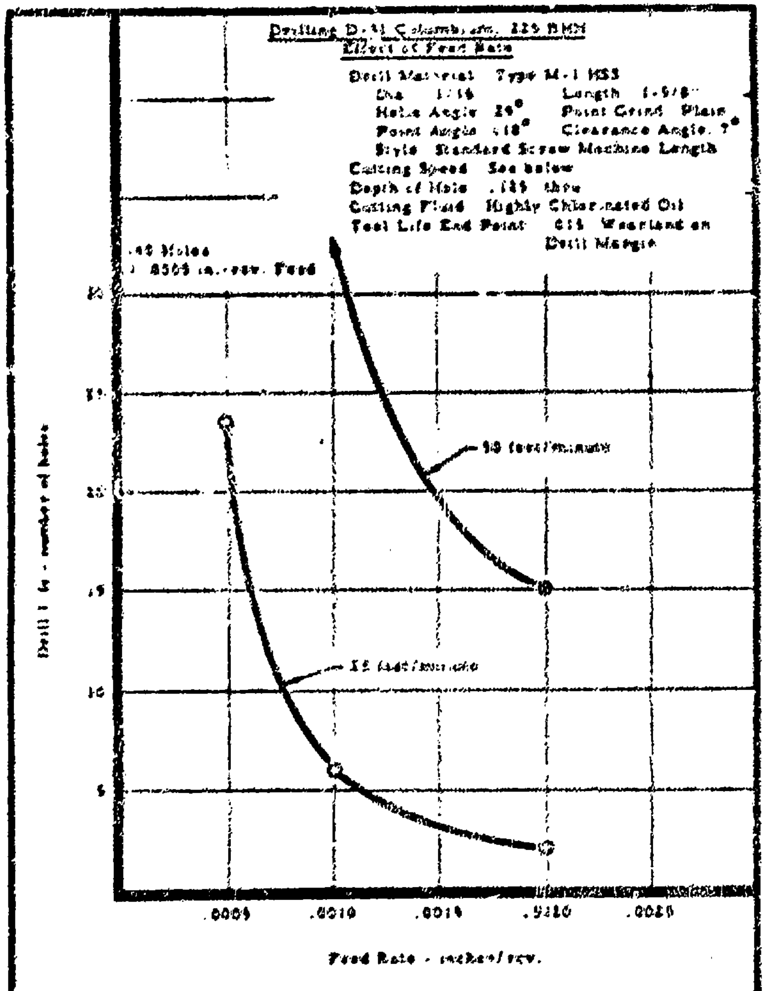
See Text page 59

Figure 70



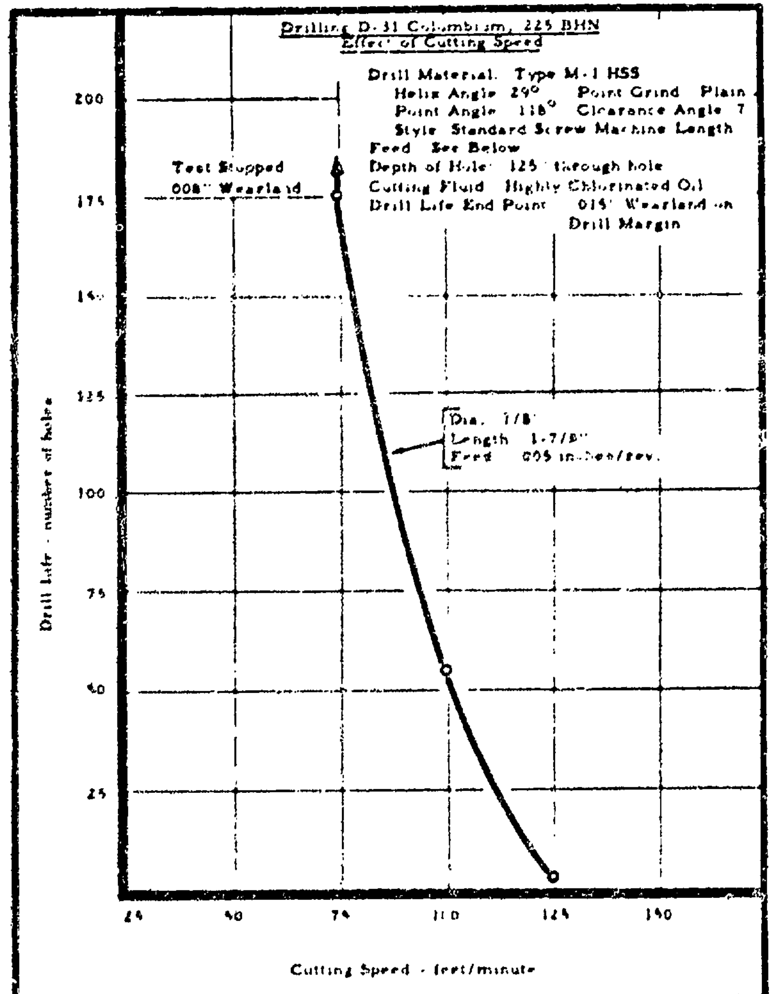
See Text page 59

Figure 71



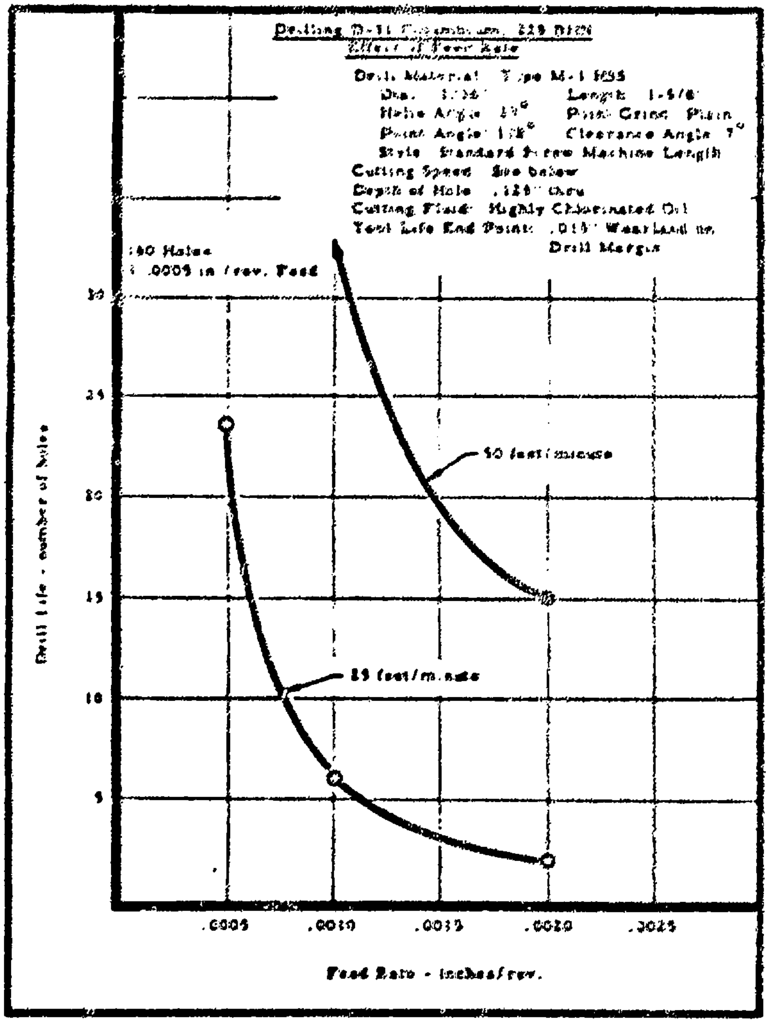
See Text page 59

Figure 72

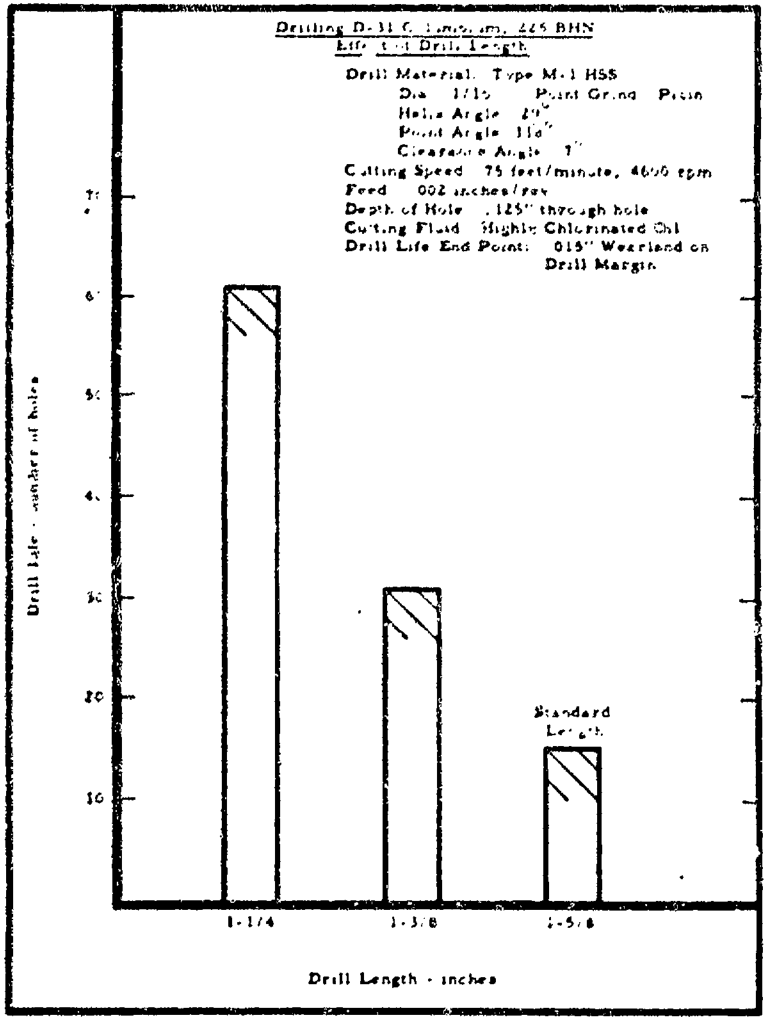


See Text page 59

Figure 73

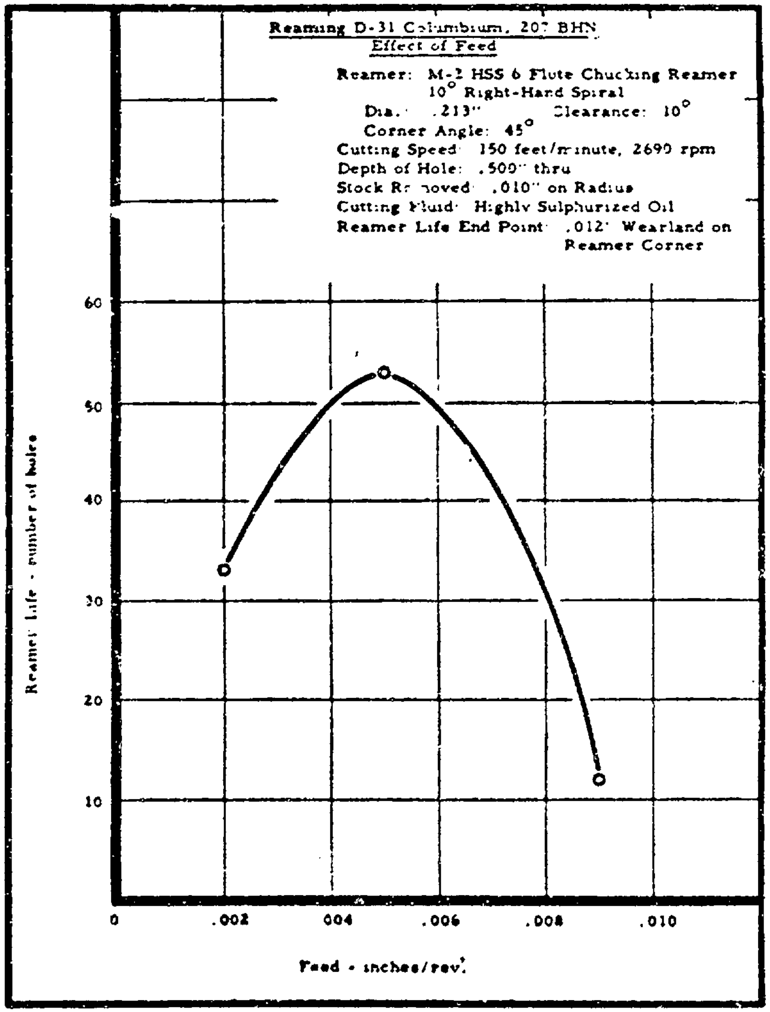


Drilling D-31 Columbium, 229 BHN
Effect of Feed Rate
Drill Material: Type M-1 HSS
Length 1-5/8"
Helix Angle 29°
Point Grind: Plain
Point Angle 118°
Clearance Angle 7°
Style: Standard Screw Machine Length
Cutting Speed: See below
Depth of Hole .125" thru
Cutting Fluid: Highly Chlorinated Oil
Tool Life End Point: .015" Wearland on Drill Margin
140 Holes
@ .0005 in./rev. Feed
50 feet/minute
35 feet/minute
Drill Life - number of holes
30
25
20
15
10
5
.0005
.0010
.0015
.0020
.0025
Feed Rate - inches/rev.



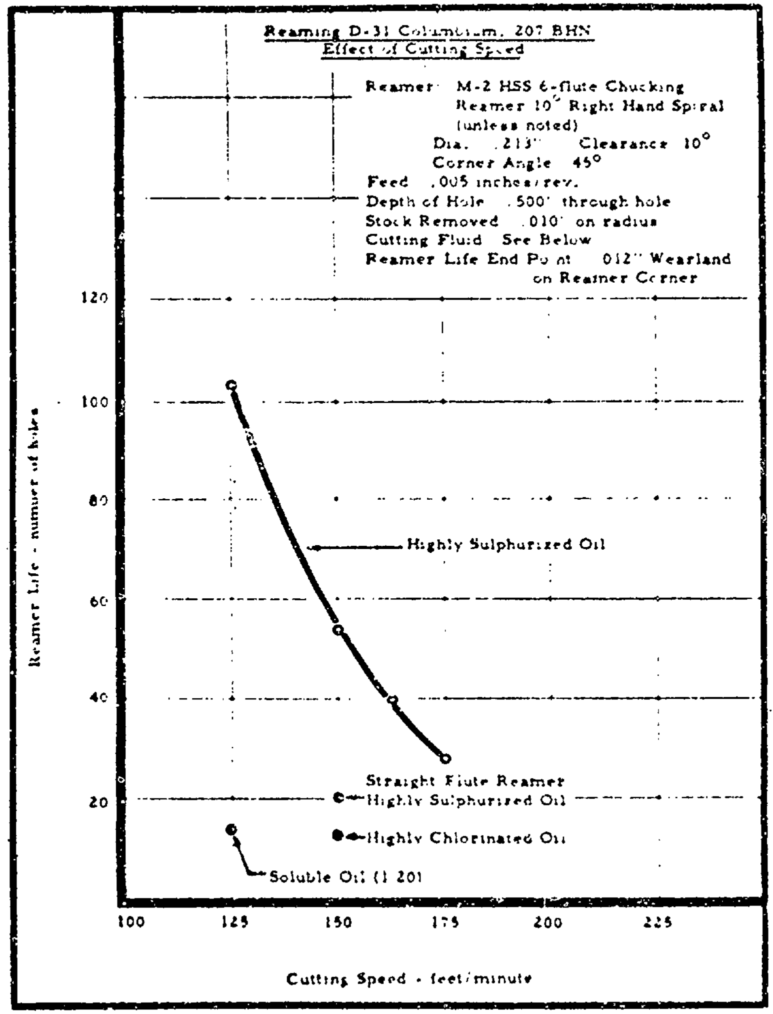
Drilling D-31 Columbium, 225 BHN
Drill Material: Type M-1 HSS
Point Grind: Plain
Helix Angle 29°
Clearance Angle 7°
Cutting Speed: 75 feet/minute, 4600 rpm
Feed .002 inches/rev
Depth of Hole .125" through hole
Cutting Fluid: Highly Chlorinated Oil
Drill Life End Point: .015" Wearland on Drill Margin
Standard Length
Drill Life - number of holes
20
10
1-1/4
1-3/8
1-5/8
Drill Length - inches

Figure 74



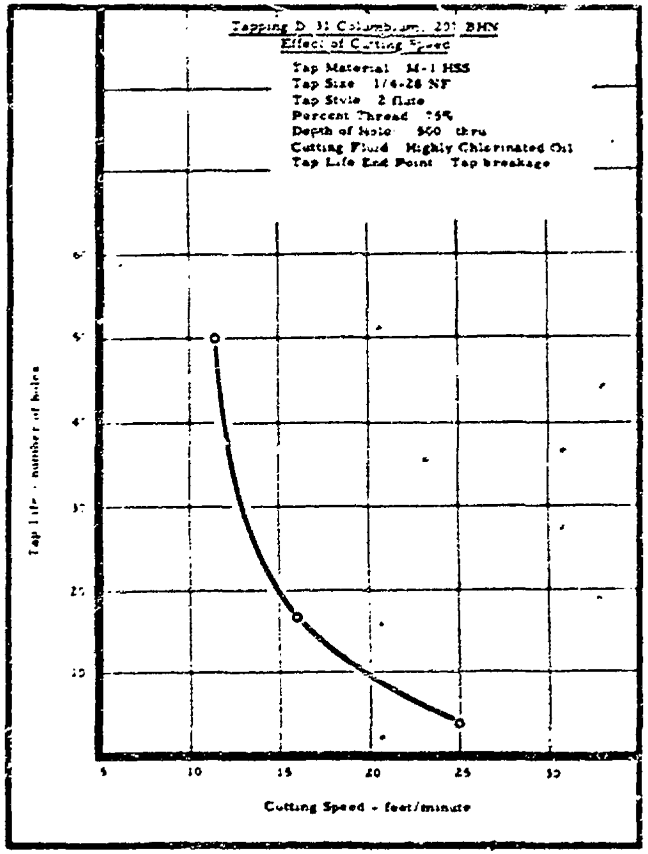
See Text page 59

Figure 77



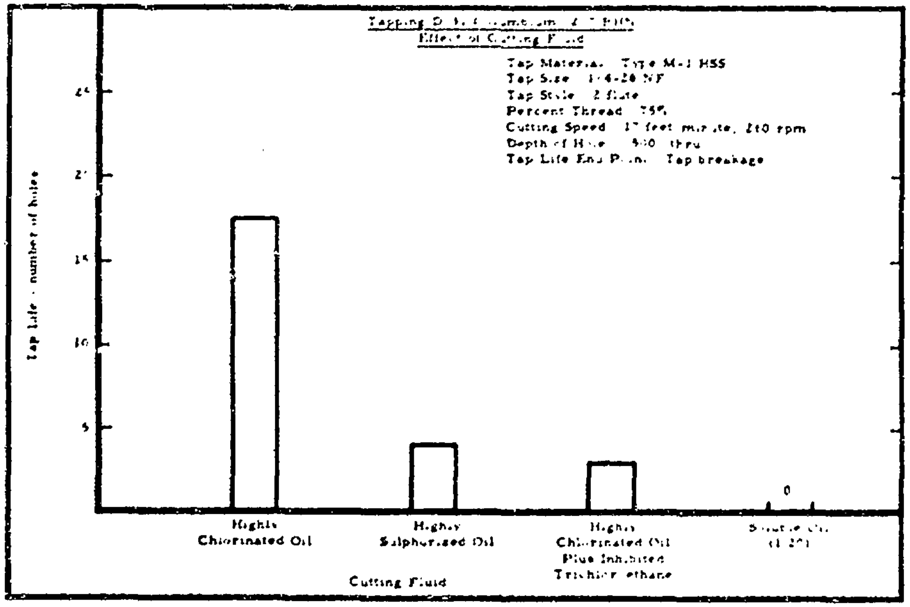
See Text page 59

Figure 78



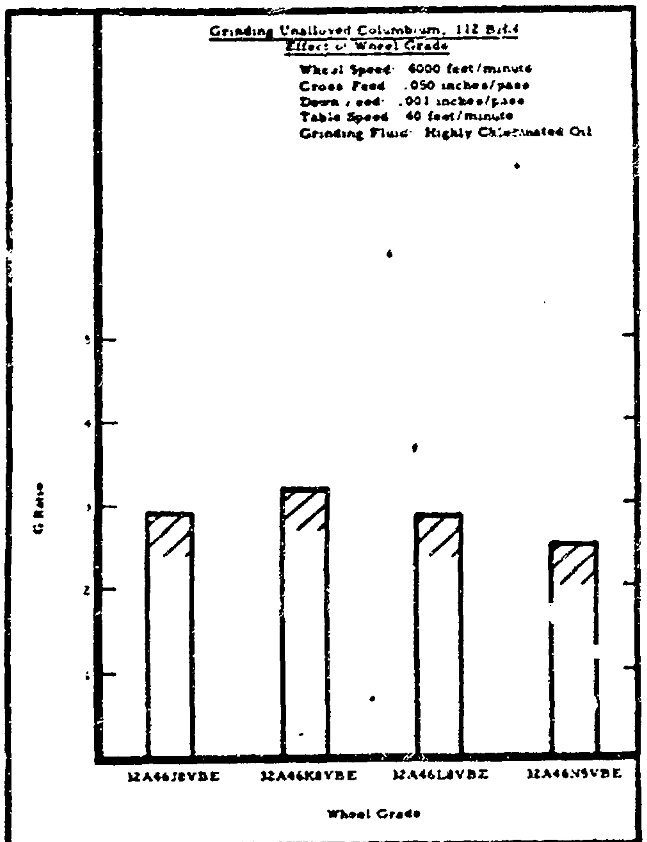
See Text page 60

Figure 78



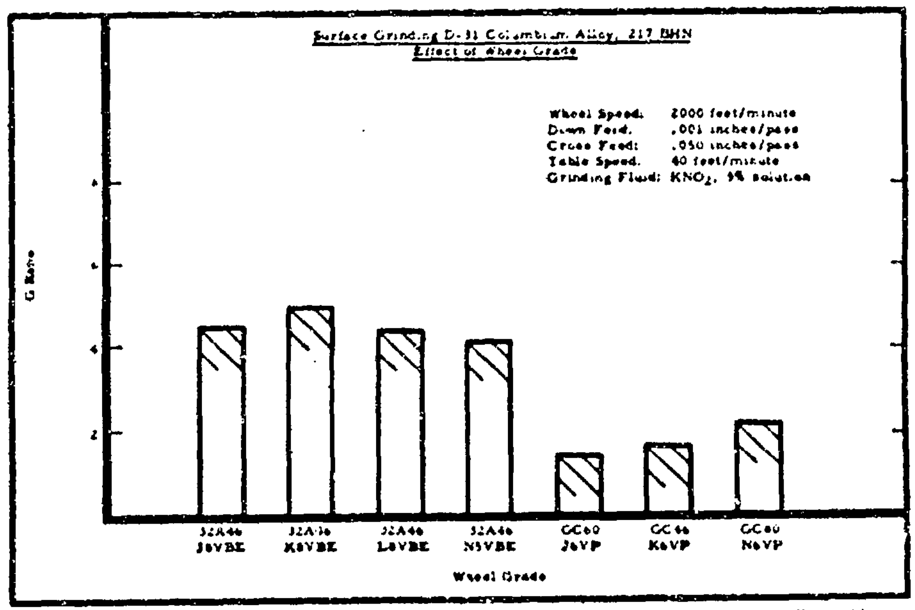
See Text page 60

Figure 7[illegible]



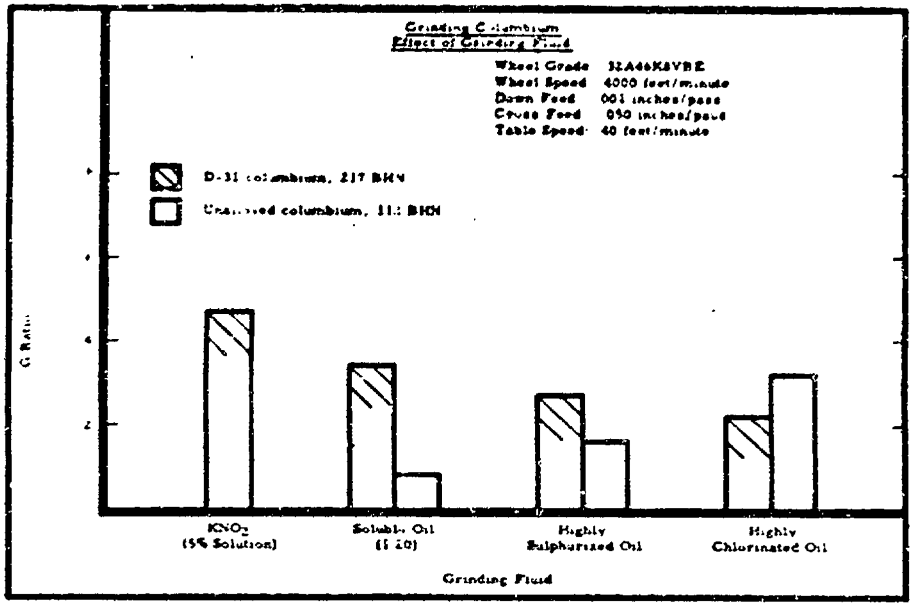
See Text page 60

Figure 80



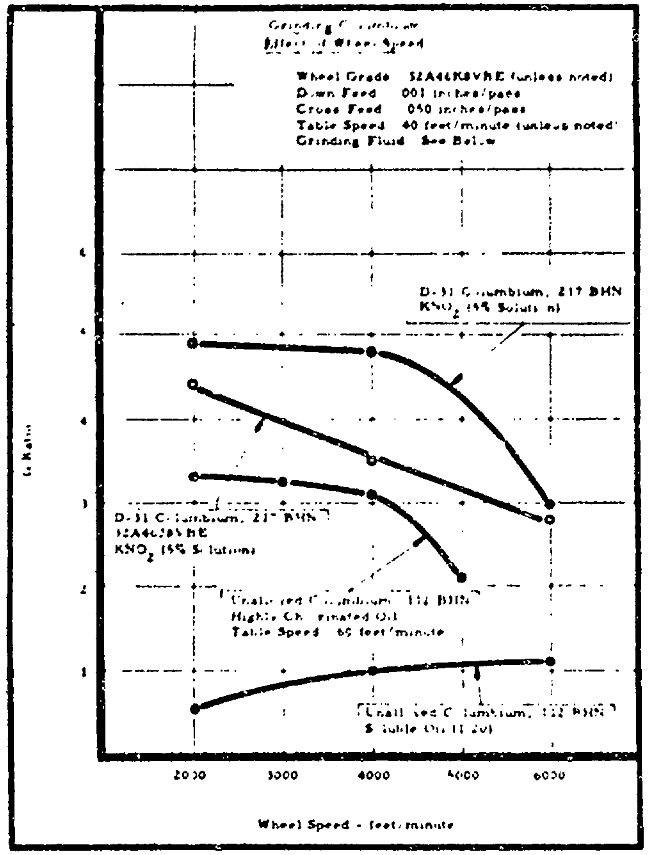
See Text, page 60

Figure 81



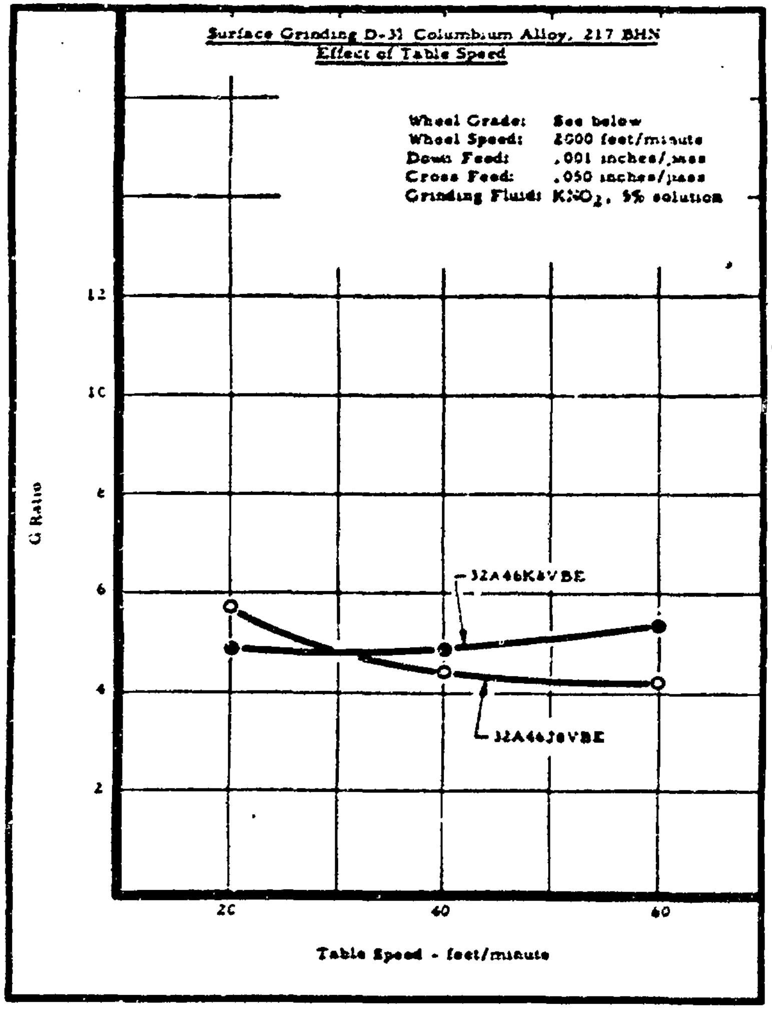
See Text, page 60

Figure 82



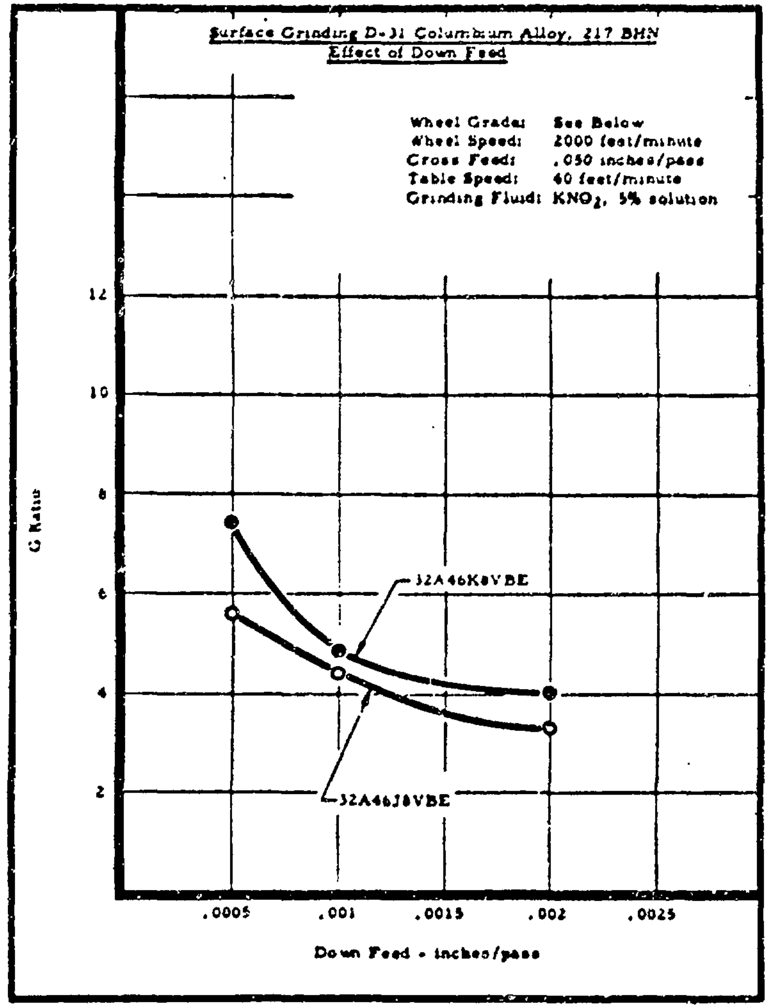
See Text page 60

Figure 83



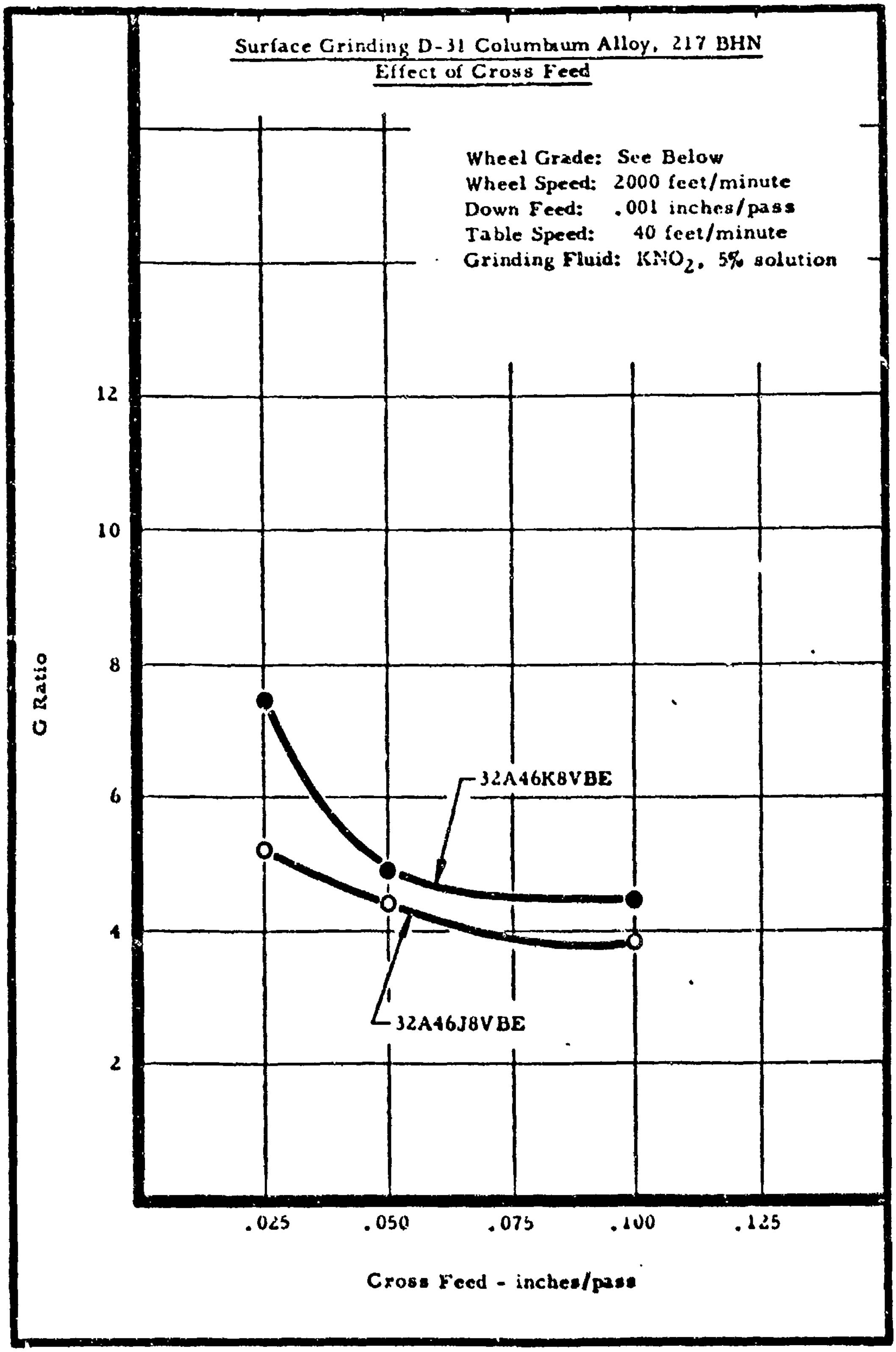
See text, page 60

Figure 64



See text, page 60

Figure 65



See text, page 60

Figure 85

V. MACHINING MOLYBDENUM - TZM ALLOY

The refractory metals are becoming increasingly important as structural materials in high speed aircraft and missiles. Molybdenum alloys in particular are being used for these applications because of their relatively high strength at temperatures in the range of 1800-2500° F, coupled with low cost in comparison to the other refractory alloys. Missile and rocket parts such as nozzles, nozzle inserts, leading edges of control surfaces and heat radiation shields are typical of current applications for molybdenum.

Two alloys of molybdenum were selected for machining tests in this program; these were the titanium-zirconium alloy known as TZM and the molybdenum-0.5% titanium alloy. Typical microstructures of these alloys are shown in Figure 87, page 83. The nominal chemical composition is given in Table 5.

Table 5
Chemical Composition of Molybdenum Alloys

Material	Nominal Composition, Percentage Ti	C	Zr	Mo	Average Hardness BHN
TZM	0.50	.015	0.08	Bal	235
Mo-0.5 Ti	0.45	.020	--	Bal	220

Recommendations for Machining TZM Molybdenum Alloy

TZM molybdenum machines similar to a medium carbon alloy steel in the 30 to 35 R_c hardness range, but tool wear occurs more rapidly. The chips produced in machining are somewhat like cast iron chips. Molybdenum tends to chip out, especially in milling operations. Machines should be rigid and free from any back lash. In turning, high positive rake angles improve cutting efficiency and increase tool life. The recommendations for machining the TZM molybdenum alloy are presented in Table 6, pages 84 and 85.

Turning Tests

The relationship between tool life and cutting speed for turning the TZM molybdenum alloy is shown in Figure 88, page 86, for two different depths of cut. A tool life of 25 minutes was obtained at a cutting speed of 450 feet/minute, a feed of .009 in./rev. and a depth of cut of .030". When the depth of cut was doubled to .060", the tool life decreased to five minutes. Also, when the TZM molybdenum alloy was cut dry, the tool life decreased to as much as one-third of the value obtained with a soluble oil. The harder grade of carbide K-8 (C-3) appeared to be no better than the K-6 (C-2) grade; the 44A (C-2) grade was somewhat poorer.

Turning Tests (continued)

As indicated in Figure 89, page 86, longer tool life was obtained with lighter feeds. At a feed of .005 in./rev., the tool life was 41 minutes or 38 cubic inches, as compared to ten minutes or 22 cubic inches at a feed of .012 inches per revolution.

The chart in Figure 90, page 87, shows the superiority of soluble oil (1:20) over highly chlorinated or sulphurized oils. The improvement in tool life with a higher side rake angle is presented in Figure 91, page 87. The tool life was increased almost four times when the rake angle was increased from 7° to 20°.

Face Milling Tests

Because molybdenum tends to chip out during machining, negative rake angle cutters should not be used in milling this alloy. Negative rake cutters also produce a poorer surface finish. The 0° axial rake and 0° radial rake carbide cutter used in the tests reported produced surface finish values ranging from 125 to 200 microinches, while surface finish measurements greater than 350 microinches were observed when using the negative rake cutters.

A comparison of various high speed steel and cast alloy tools is presented in Figure 92, page 88, for face milling the TZM molybdenum alloy. The tool life with the super high speed steels, T-15 and Braecut, was about 50% greater than with the Types T-1 and M-2 high speed steels. While the cast alloy tools showed some advantage over the T-1 and M-2 tools in one instance, these tools were poorer than the super high speed steels.

Although the feed is not critical as it affects tool life with high speed steel tools in face milling, there is some advantage in using a feed of .010 in./tooth as shown in Figure 93, page 88. Also note in Figure 94, page 89, that a 25% decrease in tool life occurred when the depth of cut was increased from .030" to .060". However, the higher production rate with the .060" depth of cut more than compensates for the decrease in tool life.

From the results shown in Figure 95, page 89, tool geometry with high speed steel tools is a very important factor influencing tool life. Negative rake angles should not be used in milling TZM molybdenum. High positive radial rake angles provide maximum tool life.

The tool life curves in Figure 96, page 90, show that a practical cutting speed for face milling the extruded TZM molybdenum alloy is 300 to 350 feet/minute with a C-2 grade carbide tool. With carbide tools, the depth of cut does not influence tool life significantly. Increasing the depth of cut from .030" to .060" resulted in a reduction in tool life of less than 10%. It should be noted that the tool life was appreciably poorer on the recrystallized, hot rolled and stress relieved alloy at the lower cutting speeds.

Face Milling Tests (continued)

As indicated in Figure 97, page 90, soluble oil (1:20) was a considerably better cutting fluid, compared with highly chlorinated oil, and far superior to face milling dry with carbide tools.

Negative rake angles should not be used with carbide cutters for face milling the TZM molybdenum alloy, see Figure 98, page 91. The optimum tool geometry is 0° axial rake and 0° radial rake. Higher positive rake angles also result in decreasing tool life. The feed was more critical with carbide tools. Note in Figure 99, page 91, that tool life decreased about 60% when the feed was increased from .005 to .008 in./tooth.

End Milling

The TZM molybdenum alloy at 248 BHN was slot milled at relatively high cutting speeds with high speed steel cutters, as shown by the tool life curves in Figure 100, page 92. A tool life of 70 inches work travel was obtained with an M-3 HSS cutter at a cutting speed of 160 feet/minute. The cutting speed could be increased to 190 feet/minute with a T-15 HSS cutter for the same tool life.

As shown in Figure 101, page 92, the type of cutting fluid used in end milling the TZM molybdenum alloy is not critical. The differences in the three fluids shown are not significant.

Heavier feeds should be employed in end milling. By increasing the feed from .002 to .005 in./tooth, tool life in terms of inches of work travel was doubled, see Figure 102, page 93.

The depth of cut should not exceed about .250" for a 3/4" diameter end mill. If a depth of cut of .500" is taken, the cutter will break down rapidly and tool life will be about 50% of that obtained at a depth of .250", see Figure 103, page 93.

The cutting speed for peripheral end milling was about 50% greater than that used in slot end milling. The tool life curves in Figure 104, page 94, show that for a tool life of 80 inches of work travel the cutting speed for the same tool life in end mill slotting was 150 feet/minute, as compared to 250 feet/minute for peripheral milling.

Drilling

The tool curve in Figure 105, page 94, shows that when the feed is increased from .005 to .009 in./rev., the drill life decreases from 98 to 34 holes. In drilling TZM molybdenum, the highly chlorinated oil showed a slight advantage over both the highly sulphurized oil and soluble oil at a drilling speed of 125 feet per minute, see Figure 106, page 95.

Drilling (continued)

The bar chart in Figure 107, page 95, illustrates the importance of drill geometry. The split point was the best in most cases and the 135° point angle was superior to all of the other point angles. Of all of the grades of high speed steel drills tested, the premium grades proved the best, as demonstrated in Figure 108, page 96.

The drill life curves obtained on several TZM molybdenum alloys which were processed differently are shown in Figure 109, page 96. The drill life on the extruded and recrystallized (220 BHN) alloy was appreciably better than that obtained on the extruded (229 BHN) only, or the extruded, recrystallized, hot rolled and stress relieved (248 BHN).

Reaming

All of the reamed holes were periodically checked for size during the tests. The hole size did not change more than .001" before a wearland of .012" was observed on the reamer. A highly polished surface is not produced in the reamed holes in this alloy. The hole surface is very similar to the dull matte finish produced in cast iron.

The tool life curves in Figure 110, page 97, indicate that the optimum feed for reaming is .015 in./rev. over a range of cutting speeds. At lower and higher feeds, reamer life was poorer. The reaming speed should be 50 to 60 feet/min. As shown in Figure 111, page 97, a highly chlorinated oil proved superior to the other two types of cutting fluids tested.

Tapping

The tapping tests reported herein were discontinued when a Class 2 plug gage would not enter the tapped hole.

The effect of cutting speed and tap style on tapping TZM molybdenum is demonstrated in Figure 112, page 98. From the chart, it appears that the optimum cutting speed was 70 feet/minute. Tap life decreased at very low cutting speeds and also at higher cutting speeds. Four flute plug taps proved effective, although at the proper cutting speed the 2 flute chip driver plug tap performed almost as well. Active cutting oils must be used in order to get a reasonable tap life. A comparison of active cutting oils with soluble oil is presented in Figure 113, page 98.

Grinding

Surface cracking does not appear to be a serious problem when grinding molybdenum. However, grinding wheels tend to load very rapidly and require frequent dressing. A severe chatter condition will occur if a loaded wheel is used. Surface

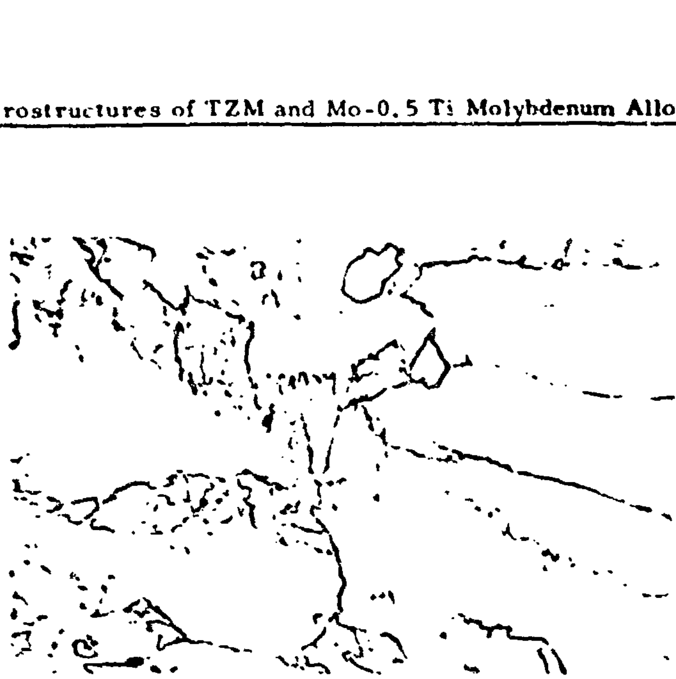
finish measurements in the range of 10 to 35 microinches, depending on the grinding conditions used, were obtained when grinding this alloy.

The relative merits of several grades of grinding wheels for grinding the TZM molybdenum alloys are shown in Figure 114, page 99. At a wheel speed of 5000 feet/minute and using a soluble oil, the harder grade 32A46N5VBE wheel produced the highest G ratio. However, chatter occurred with these grinding conditions.

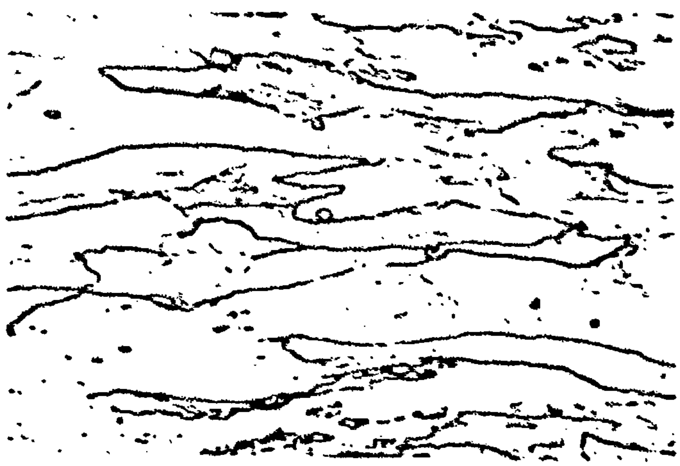
Further test results on the best three grades are presented in Figure 115, page 99. The G ratio was improved considerably by using a 5% solution of potassium nitrite at a reduced wheel speed. Under the conditions listed in Figure 115, page 99, a G ratio of 25 was obtained with the 32A46N5VBE wheel. The 5% solution of potassium nitrite also proved to be superior to active oils as shown in Figure 116, page 100. The table speed should be in the range of 20 to 50 feet/minute; the G ratio decreased at higher table speeds, see Figure 117, page 100.

As indicated in Figures 118 and 119, page 101, the down feed should not exceed .002 in./pass the the cross feed should be in the range of .050 to .100 in./pass to obtain a reasonable grinding ratio.

A nitrite grinding fluid has been selected in the table of recommended grinding conditions for this alloy. In spite of its tendency to leave salt deposits on the grinder, it was selected because of the vast improvement in grinding ratio over soluble oil and straight grinding oils.



TZM Molybdenum Alloy
Extruded, Recrystallized, Hot Rolled and
Stress Relieved, 235 BHN
Microstructure is single phase, consisting of relatively uniform grains.
Magnification: 500X Etchant: Murikami's



Mo-0.5 Ti Molybdenum Alloy
Arc Melted, Extruded, Recrystallized, Hot Rolled and
Stress Relieved, 220 BHN
Microstructure consists of single phase grains exhibiting orientation due to rolling.
Magnification: 500X Etchant: Murikami's

Figure 87

See Text, page 78

TABLE 6
RECOMMENDED CONDITIONS FOR MACHINING AND GRINDING
TZM MOLYBDENUM - 217 BHN

Nominal Chemical Composition, Percent

Ti	C	Zr	Mo
0.50	.015	0.08	Bal.

Operation	Tool Material	Tool Geometry	Tool Used for Tests	Depth of Cut inches	Width of Cut inches	Feed	Cutting Speed ft./min.	Tool Life	Wear-land inches	Cutting Fluid
Turning	C-2 Carbide	BR: 0° SCEA: 15° SR:20° ECEA: 15° Relief: 5° NR: 1/32"	5/8" square brazed tool bit	.030	-	.009 in/rev	450	25 min.	.010	Soluble Oil (1:20)
Turning	C-2 Carbide	BR: 0° SCEA: 15° SR:20° ECEA: 15° Relief: 5° NR: 1/32"	5/8" square brazed tool bit	.060	-	.009 in/rev	350	20 min.	.010	Soluble Oil (1:20)
Face Milling	T-15 HSS	AR: 0° ECEA:10° RR: 20° CA: 45° Clearance: 15°	4" diameter single tooth face mill	.060	2	.010 in/tooth	100	70 in/tooth	.015	Soluble Oil (1:20)
Face Milling	C-2 Carbide	AR: 0° ECEA: 5° RR: 0° CA: 45° Clearance: 10°	4" diameter single tooth face mill	.060	2	.005 in/tooth	350	100 in/tooth	.015	Soluble Oil (1:20)
End Mill Slotting	T-15 HSS	Helix Angle: 30° RR: 10° Clearance: 10° CA: 45°	3/4" diameter 4 tooth HSS end mill	.125	.750	.004 in/tooth	190	78 inches	.012	Soluble Oil (1:20)
End Mill Peripheral Cut	M-3 HSS	Helix Angle: 30° RR: 10° Clearance: 10° CA: 45°	3/4" diameter 4 tooth HSS end mill	.125	.750	.004 in/tooth	190	142 inches	.012	Soluble Oil (1:20)

See Text, page 78

TABLE 6 (continued)
RECOMMENDED CONDITIONS FOR MACHINING AND GRINDING
TZM MOLYBDENUM - 217 BHN

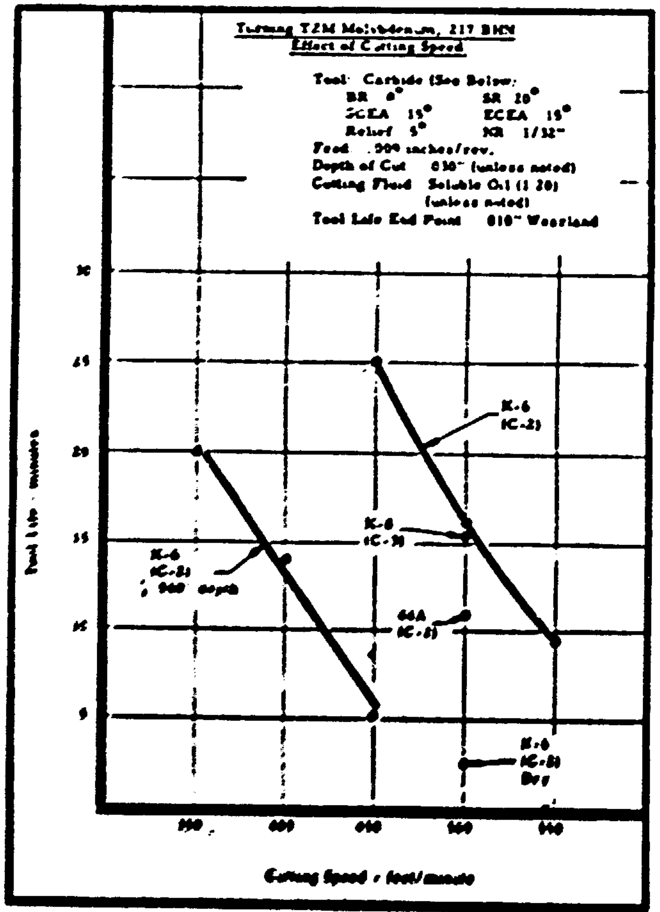
Operation	Tool Material	Tool Geometry	Tool Used for Tests	Depth of Cut inches	Width of Cut inches	Feed	Cutting Speed ft/min	Tool Life	Wear-land inches	Cutting Fluid
Drilling	M-33 HSS	118° plain point 7° clearance angle	.250" diameter drill 2-1/2" long	1/2" thru hole	-	.005 in/rev	150	68 holes	.015	Highly Chlorinated Oil
Reaming	M-2 HSS	Helix Angle: 0° CA: 45° Clearance: 10°	.272" diameter 6 flute chucking reamer	1/2" thru hole	.010" depth on hole radius	.015 in/rev	60	51 holes	.012	Highly Chlorinated Oil
Tapping	M-10 HSS	4 flute plug 75% thread	5/16-24 NF tap	1/2" thru hole	-	-	70	100+ holes	-	Highly Chlorinated Oil

SURFACE GRINDING

Wheel Grade	Grinding Fluid	Wheel Speed feet/minute	Table Speed feet/minute	Down Feed inches/pass	Cross Feed inches/pass	G Ratio
32A46N5VBE	5% KNO_2 Solution	2000*	40	.001	.050	25
32A46L8VBE	5% KNO_2 Solution	4000	40	.001	.050	13

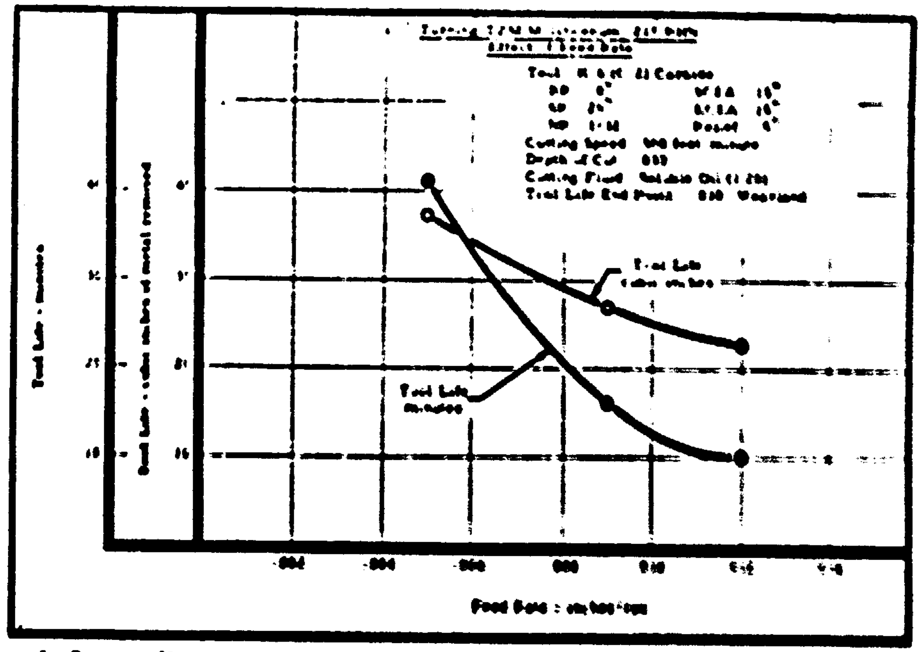
* If wheel speed of 2000 feet/minute is not available, use conditions for wheel speed of 4000 feet/minute.

See Text, page 78



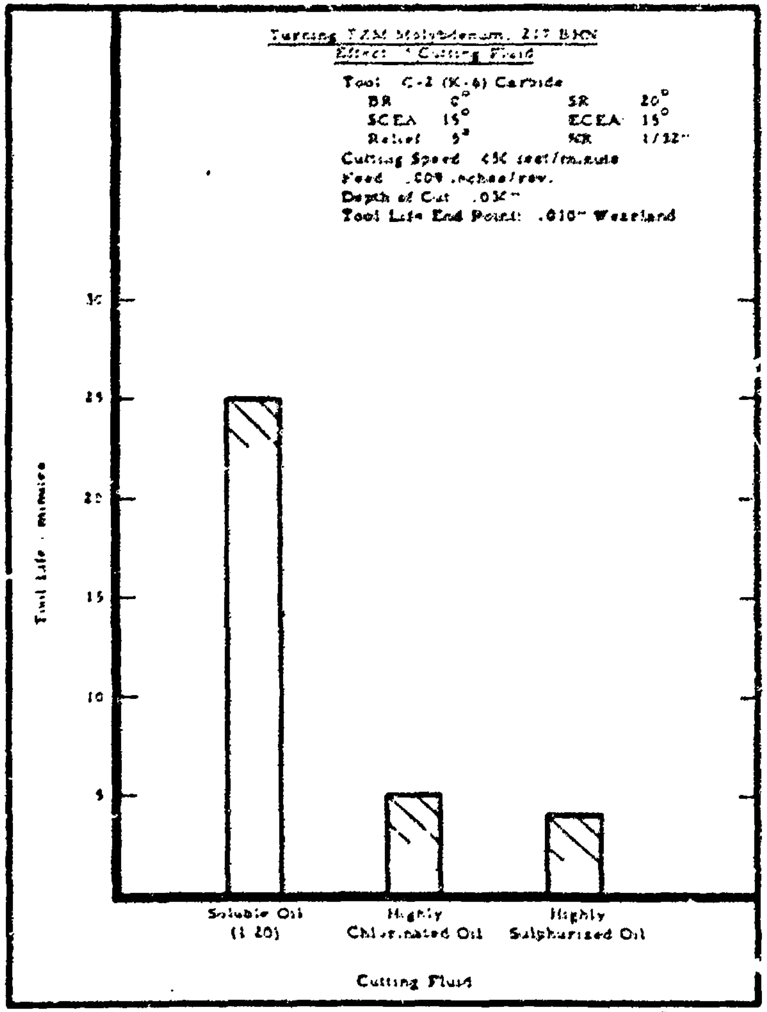
See Text page 79

Figure 80



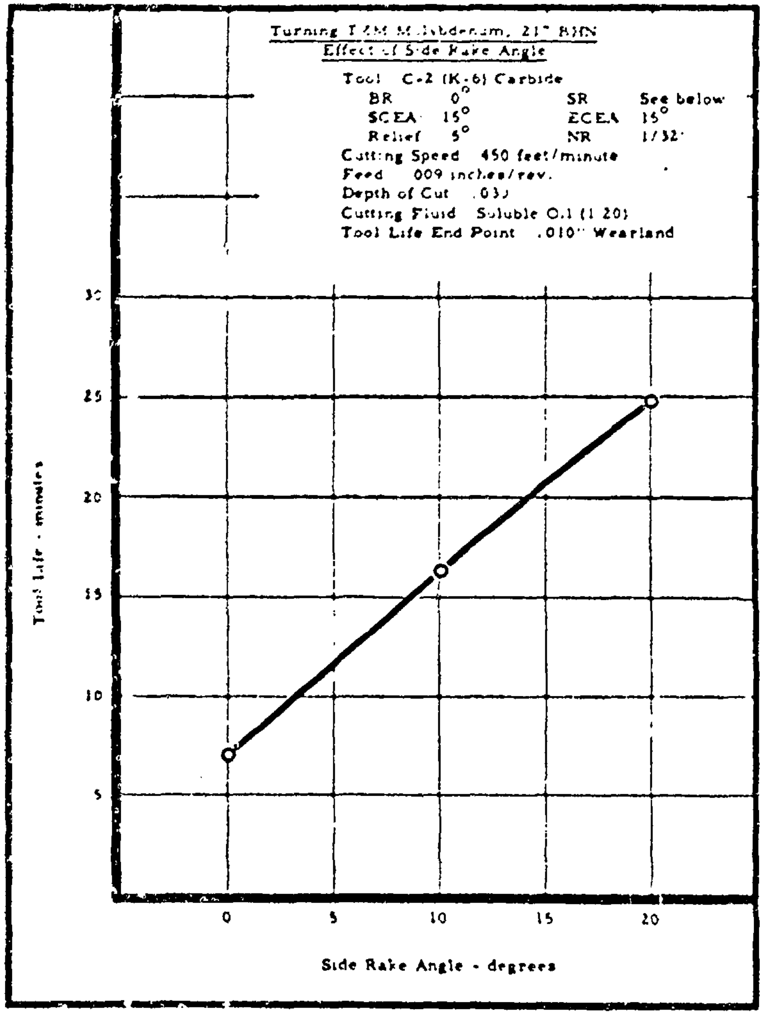
See Text page 79

Figure 81



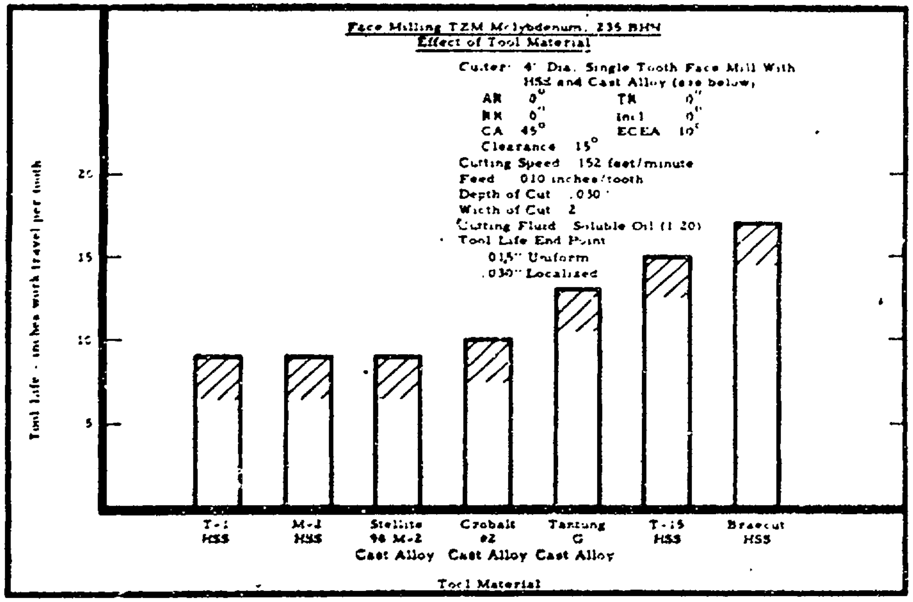
See Text page 79

Figure 90



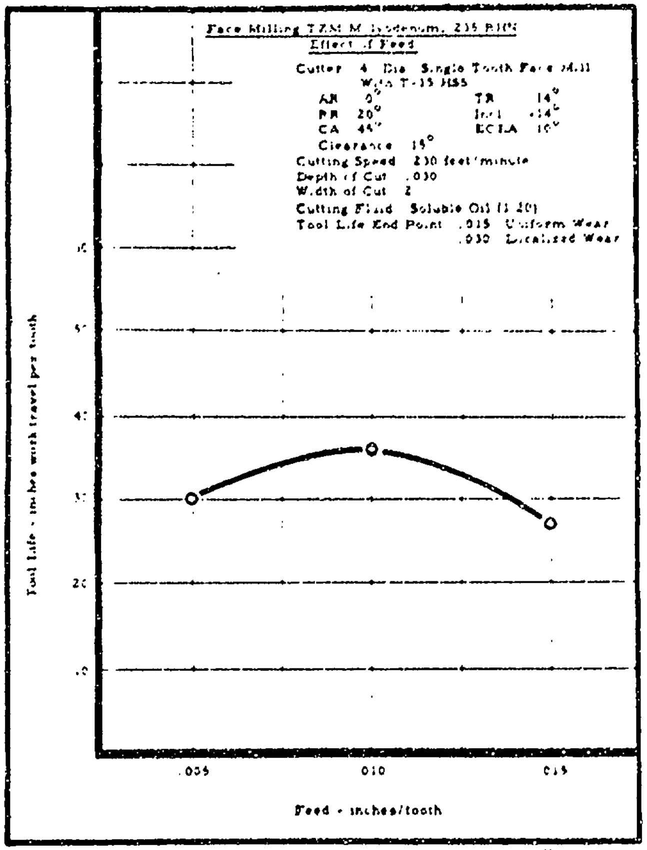
See Text page 79

Figure 91



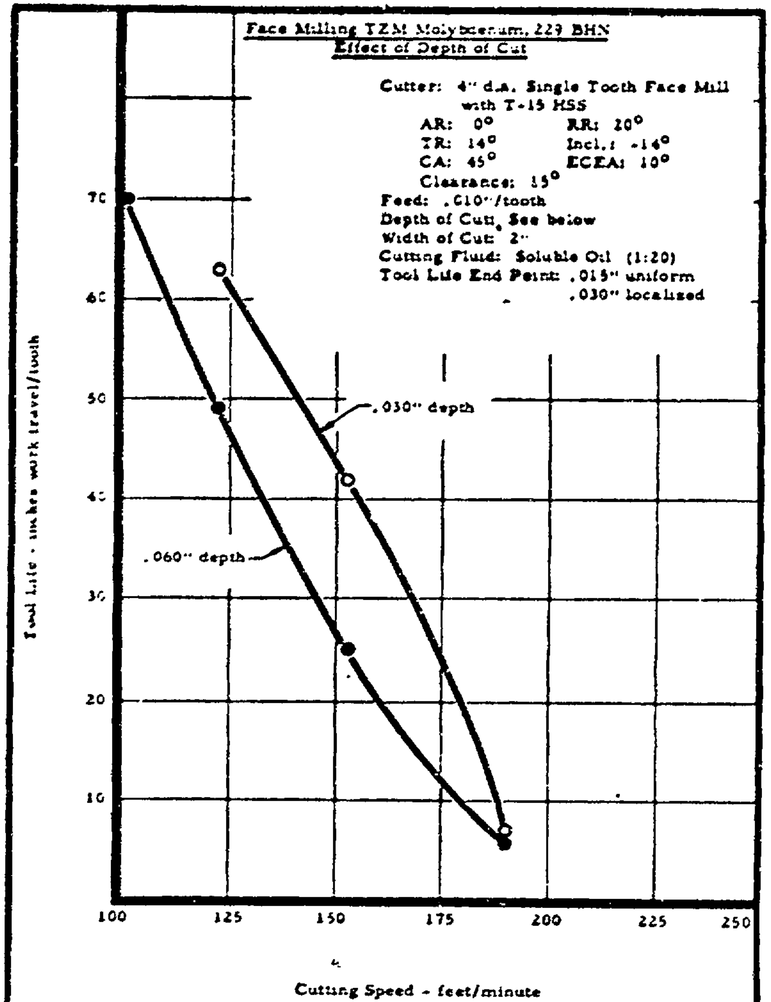
See Text page 79

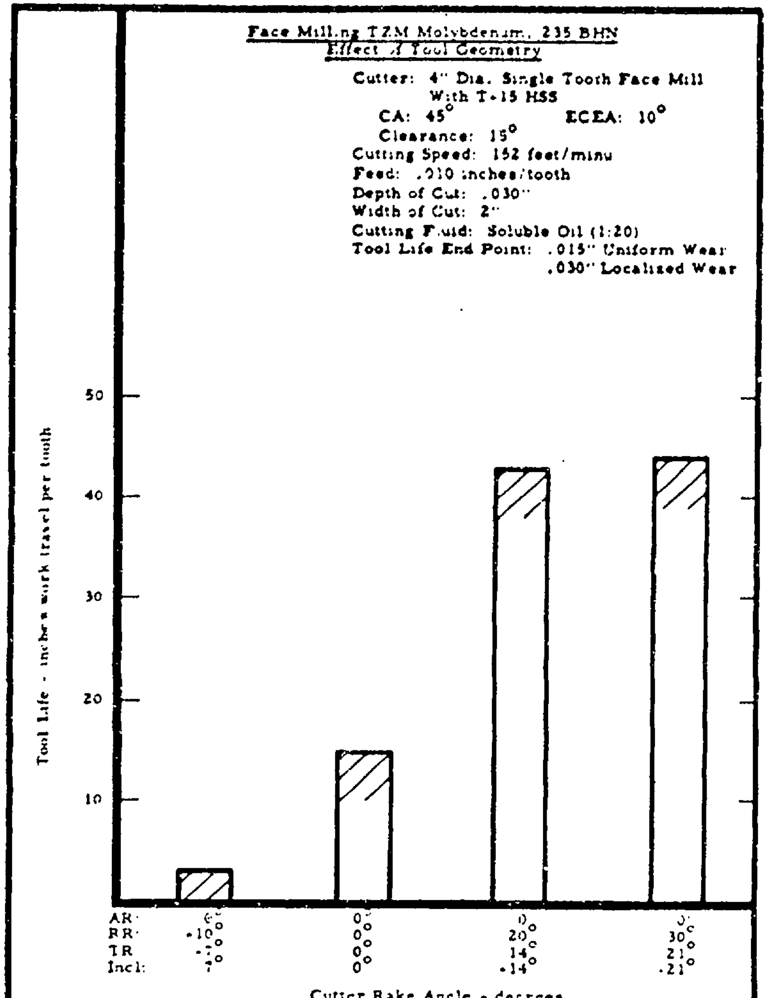
Figure 92



See Text page 79

Figure 93


Face Milling TZM Molybdenum, 229 BHN
Effect of Depth of Cut
Cutter: 4" dia. Single Tooth Face Mill with T-15 HSS
AR: 0°
RR: 20°
TR: 14°
Incl.: -14°
CA: 45°
ECEA: 10°
Clearance: 15°
Feed: .010"/tooth
Depth of Cut: See below
Width of Cut: 2"
Cutting Fluid: Soluble Oil (1:20)
Tool Life End Point: .015" uniform
.030" localized
.030" depth
.060" depth
Tool Life - inches work travel/tooth
Cutting Speed - feet/minute
100
125
150
175
200
225
250
10
20
30
40
50
60
70


Face Milling TZM Molybdenum, 235 BHN
Effect of Tool Geometry
Cutter: 4" Dia. Single Tooth Face Mill With T-15 HSS
CA: 45°
ECEA: 10°
Clearance: 15°
Cutting Speed: 152 feet/minu
Feed: .010 inches/tooth
Depth of Cut: .030"
Width of Cut: 2"
Cutting Fluid: Soluble Oil (1:20)
Tool Life End Point: .015" Uniform Wear
.030" Localized Wear
Tool Life - inches work travel per tooth
10
20
30
40
50
AR
RR
TR
Incl:
-10°
0°
20°
14°
-14°
30°
21°
-21°
Cutter Rake Angle - degrees

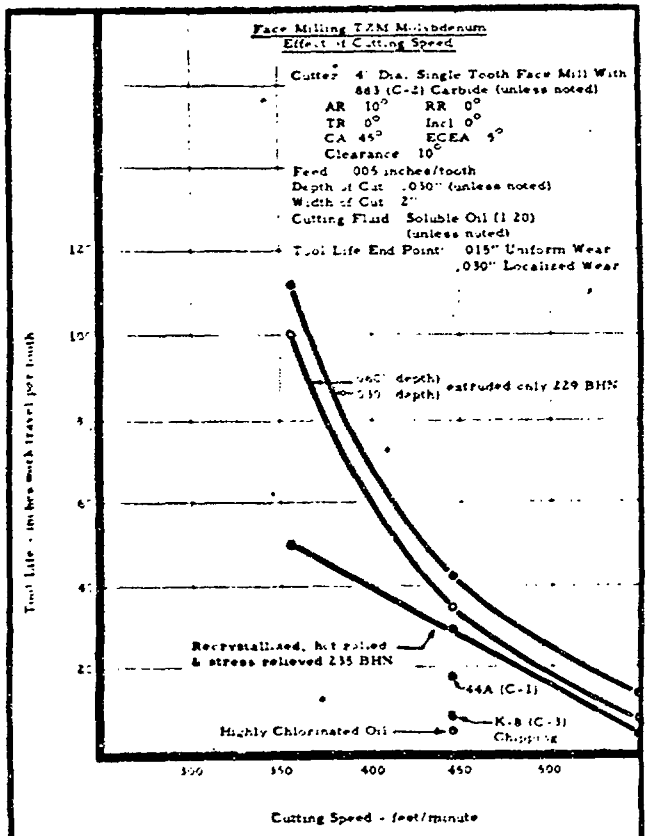


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Figure 96

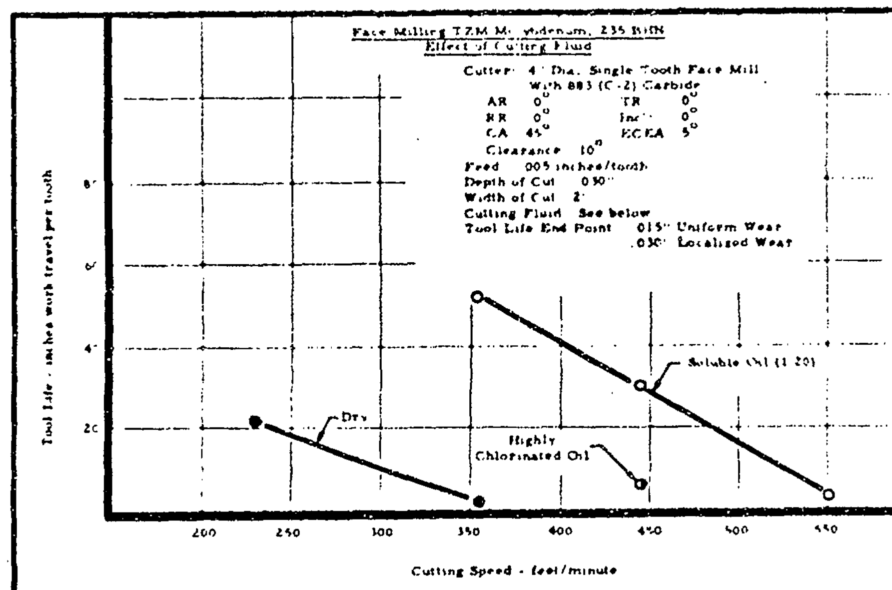

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Figure 97

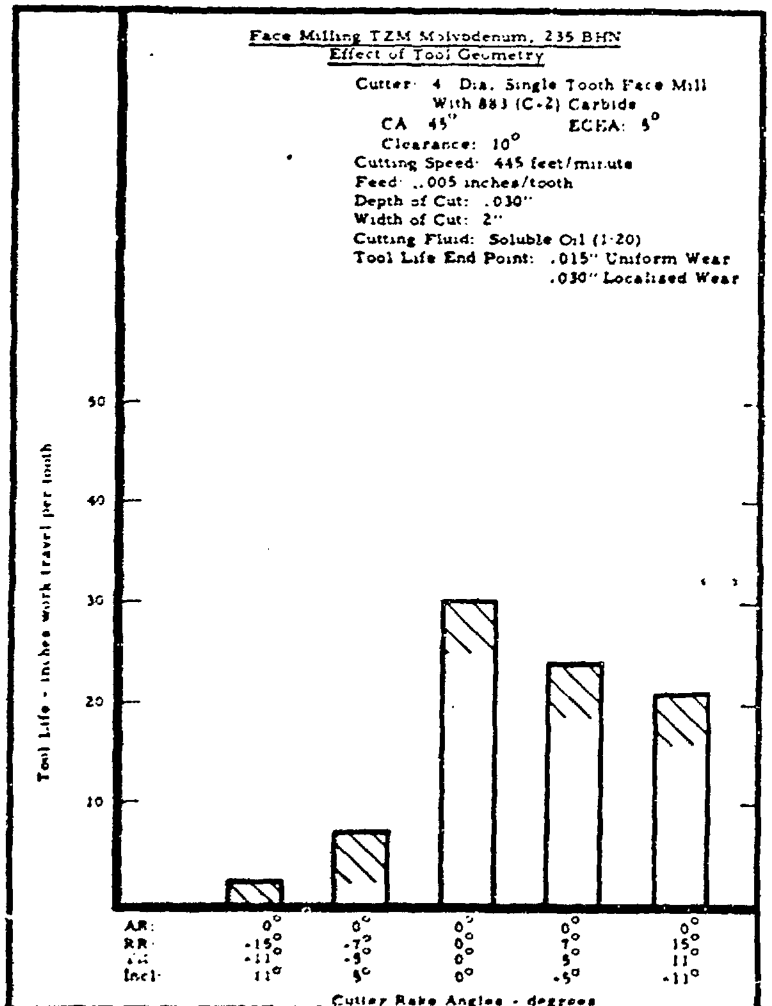

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Figure 98

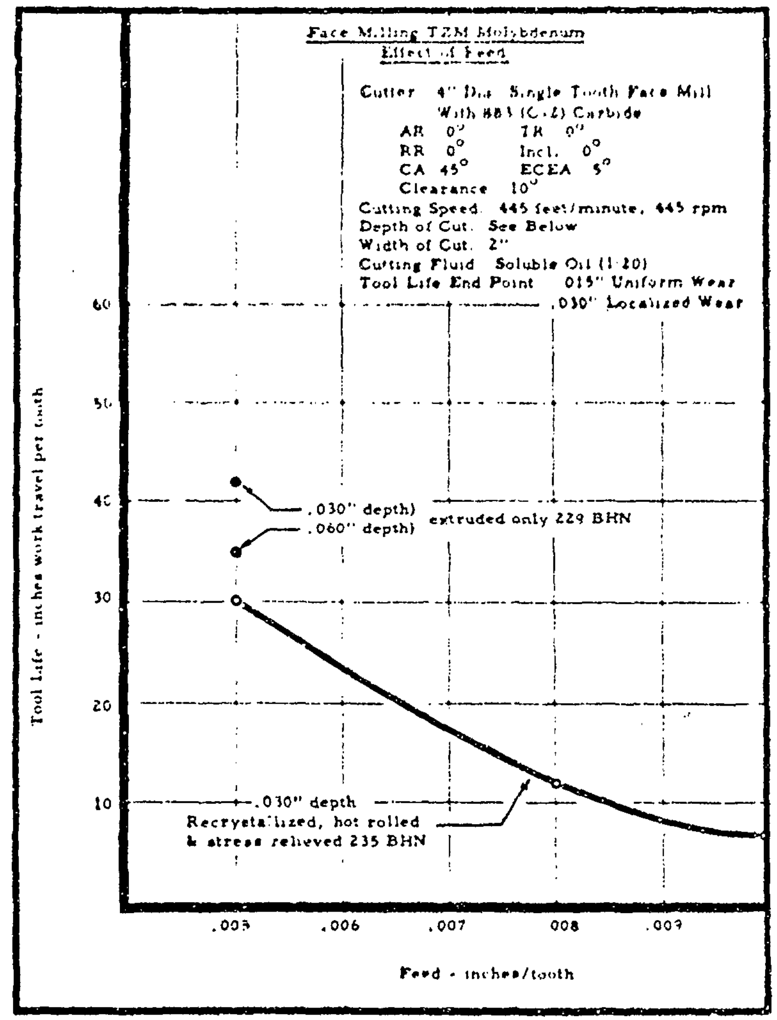

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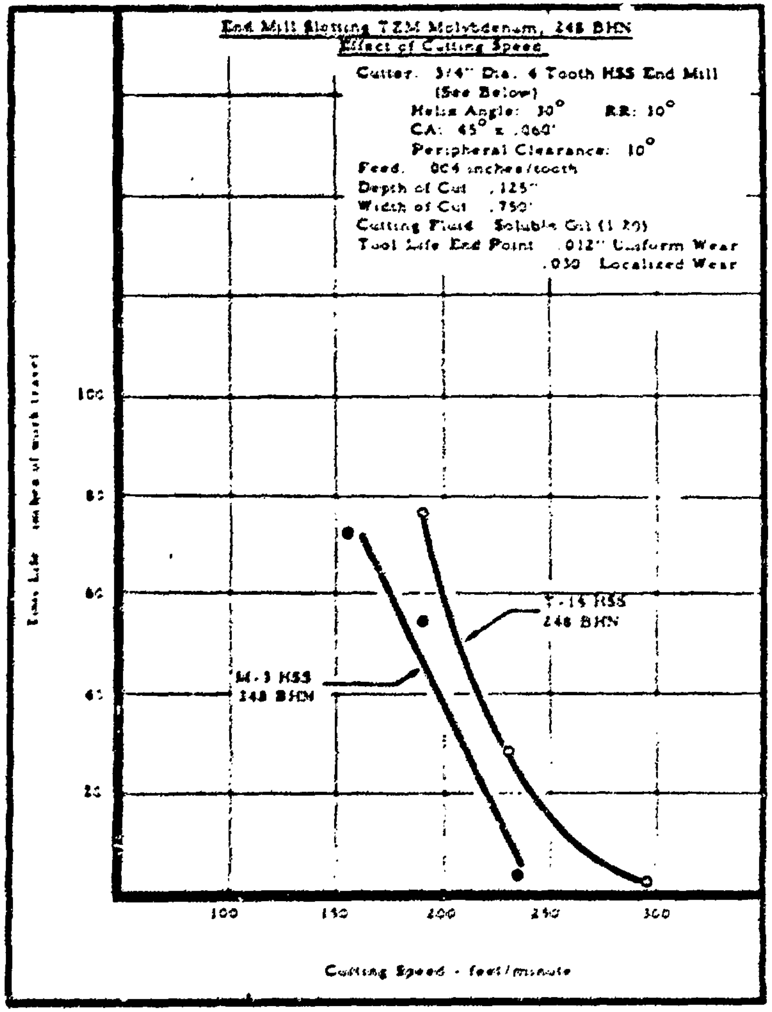
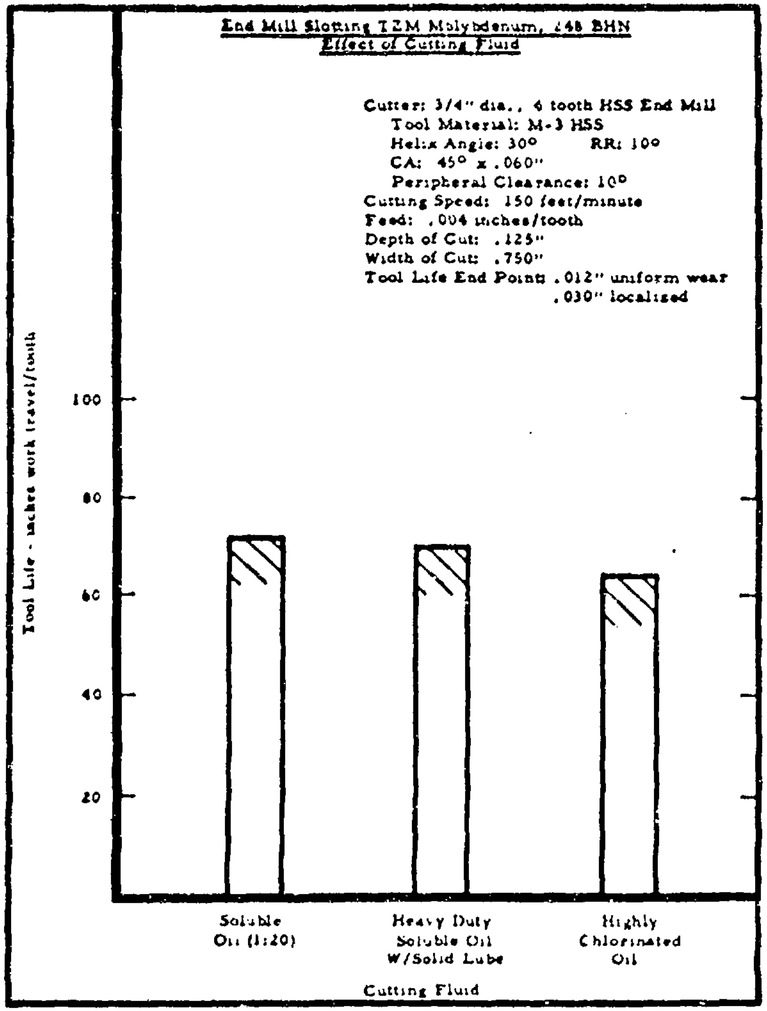
Figure 99



See Text page 80 Figure 100



See text, page 80 Figure 101

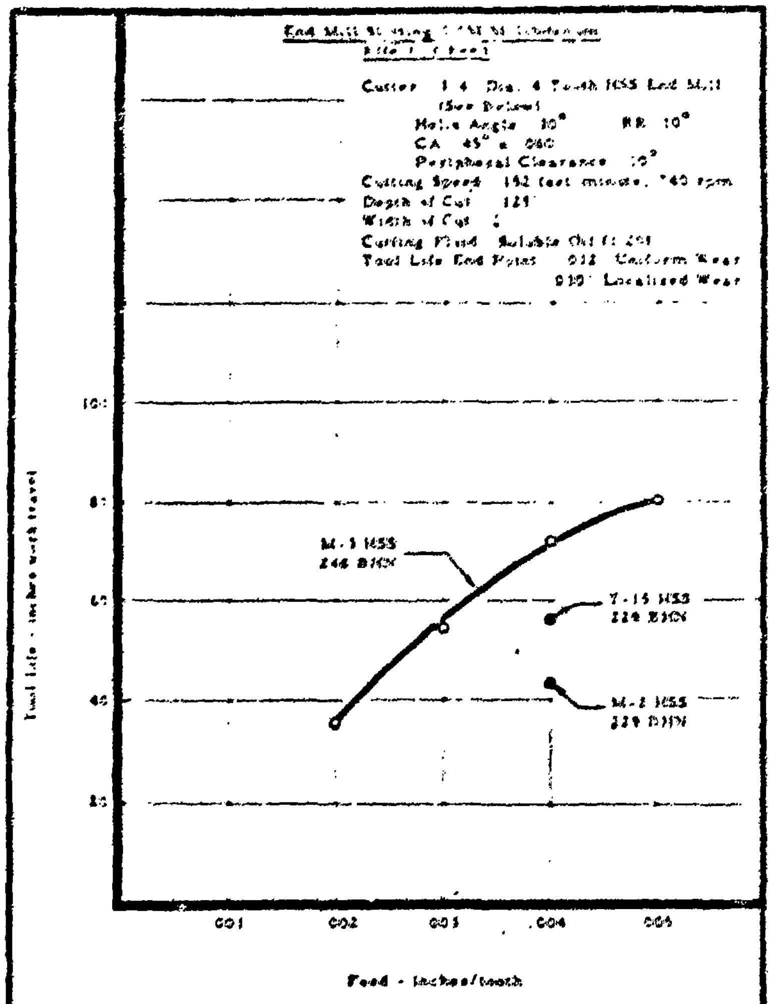


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Figure 102.

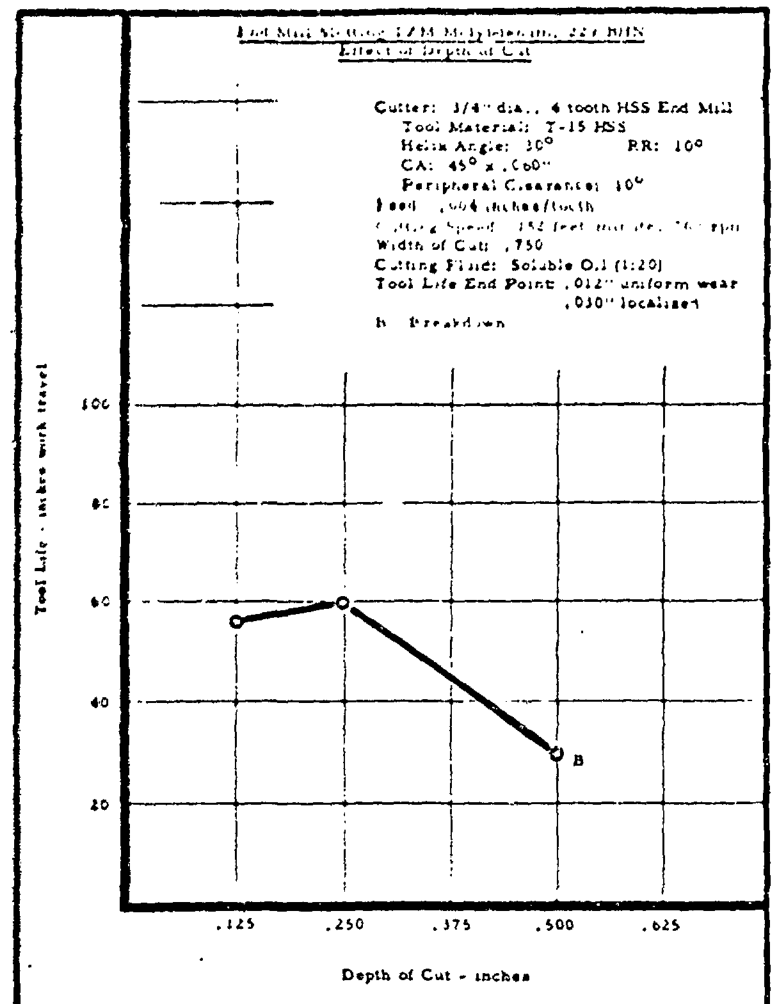

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Figure 103

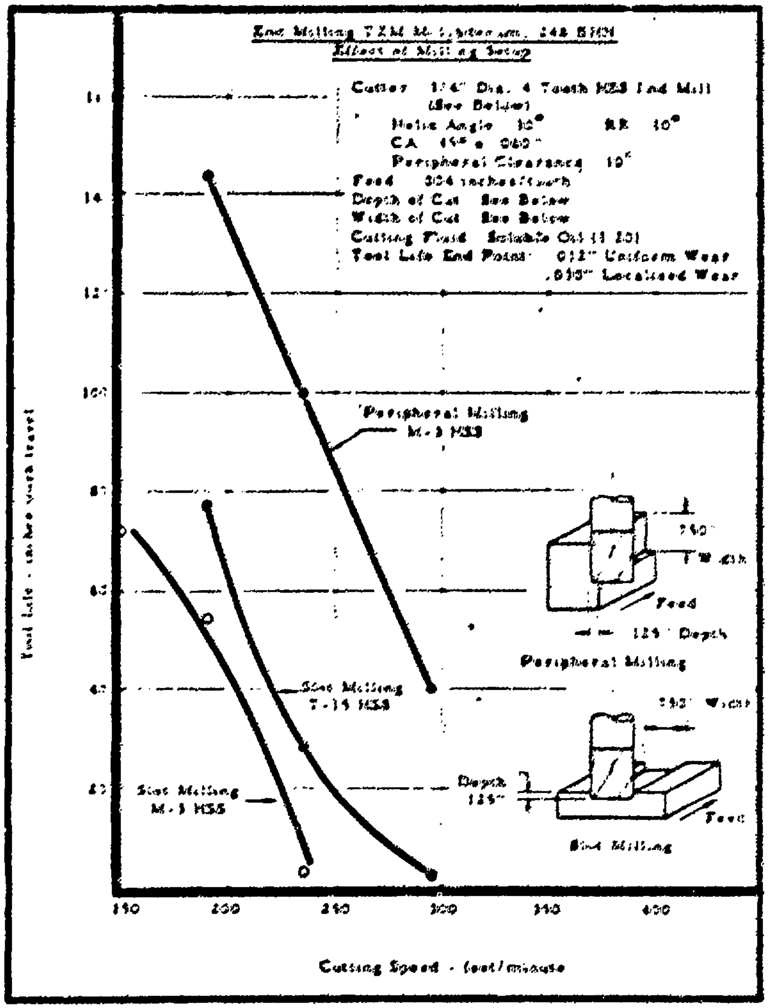

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Figure 104

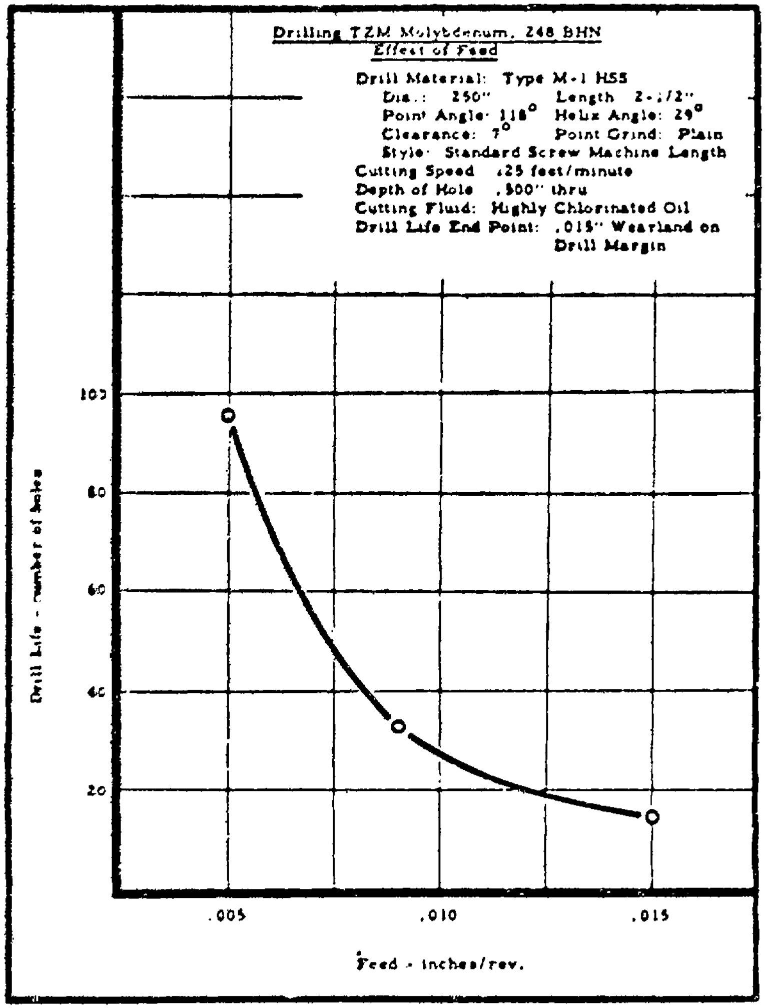

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Figure 10-

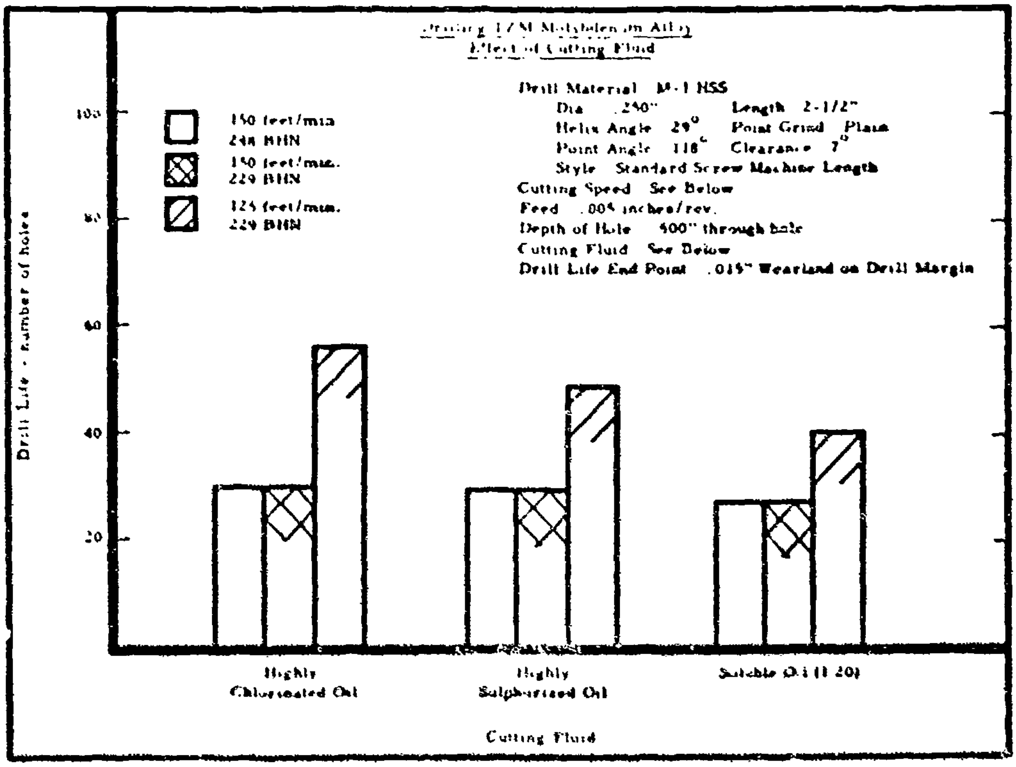

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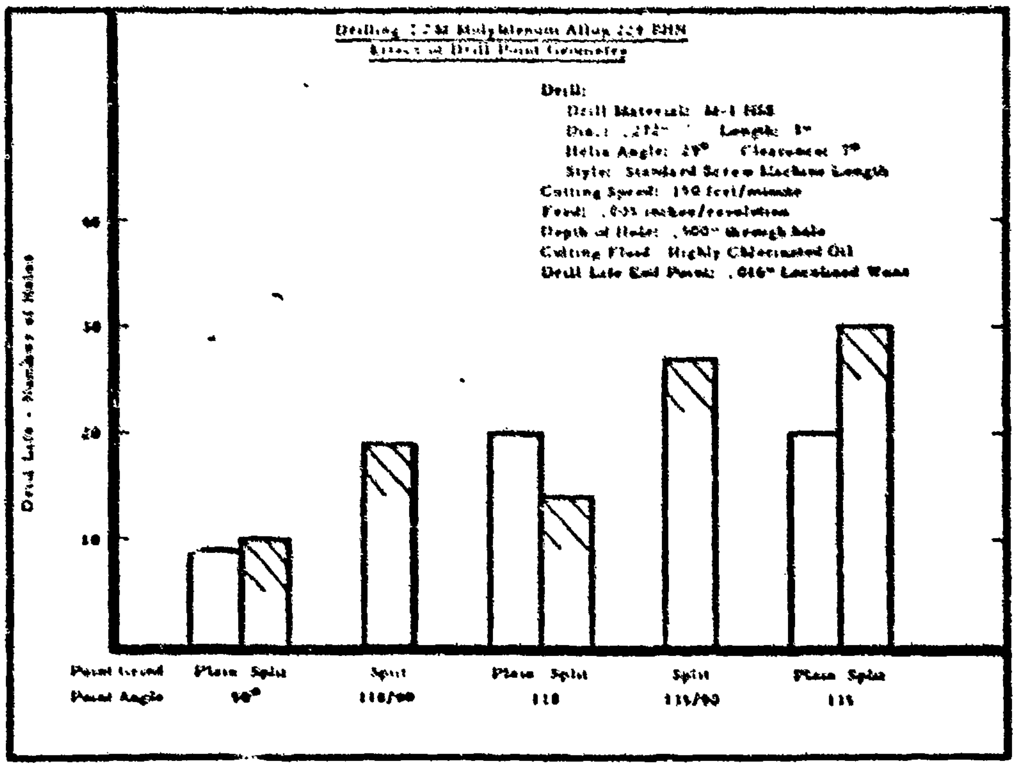
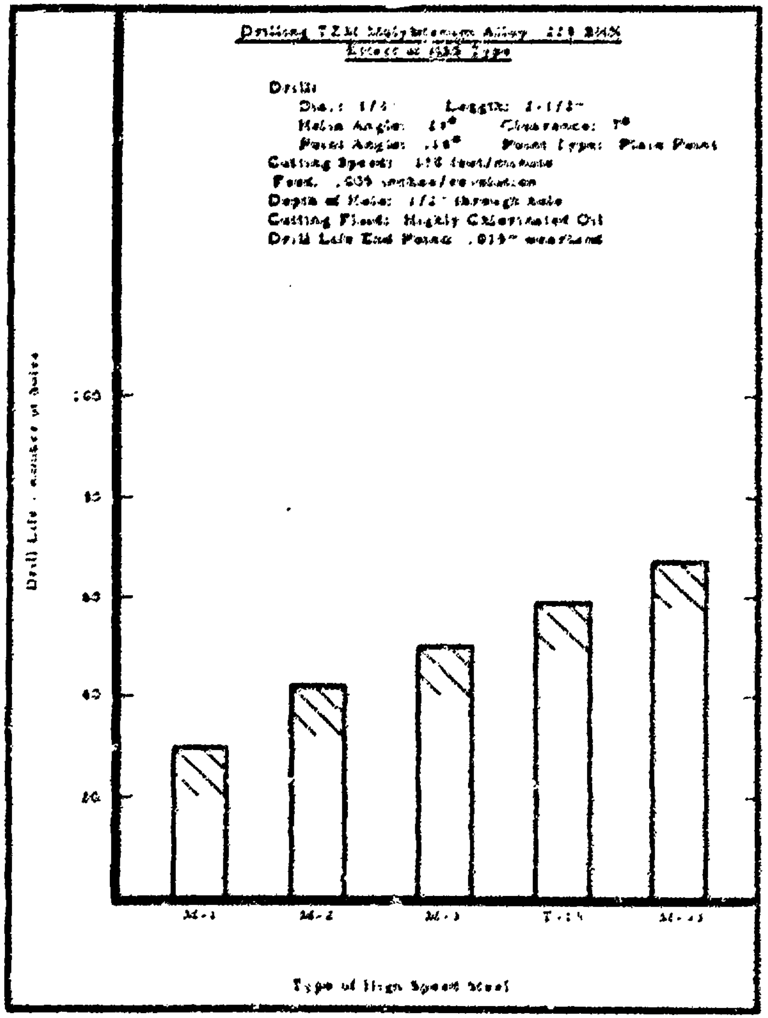
Figure 106



See Text, page 81

Figure 107



See text, page 81

Figure [illegible]

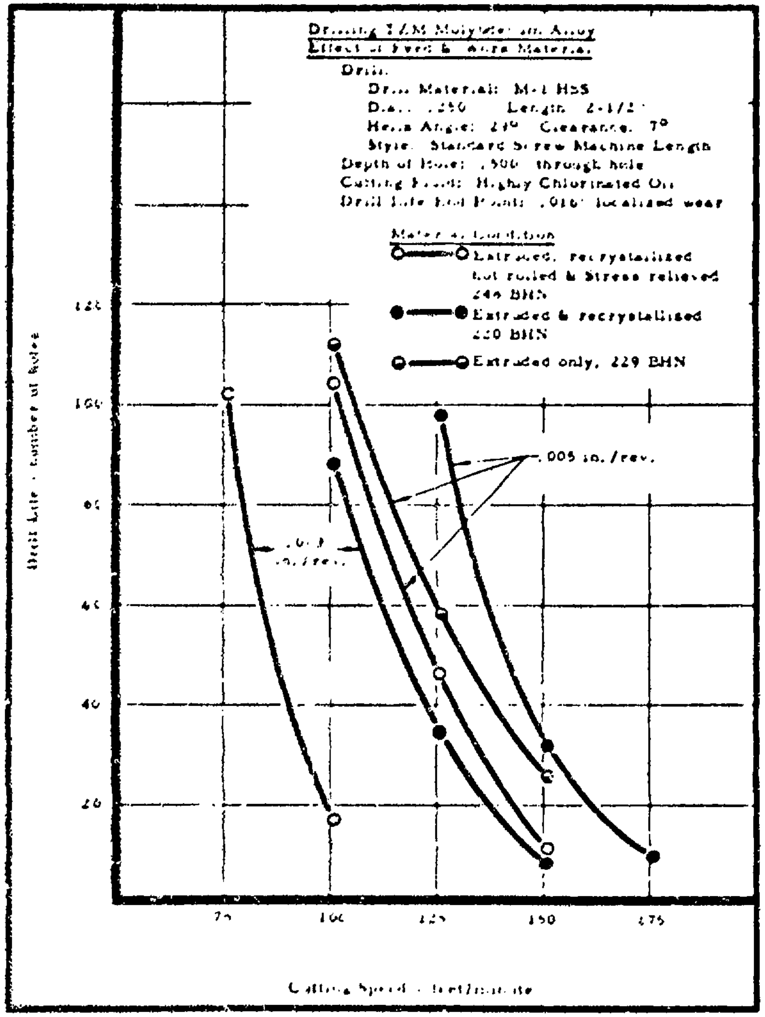


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Figure [illegible]

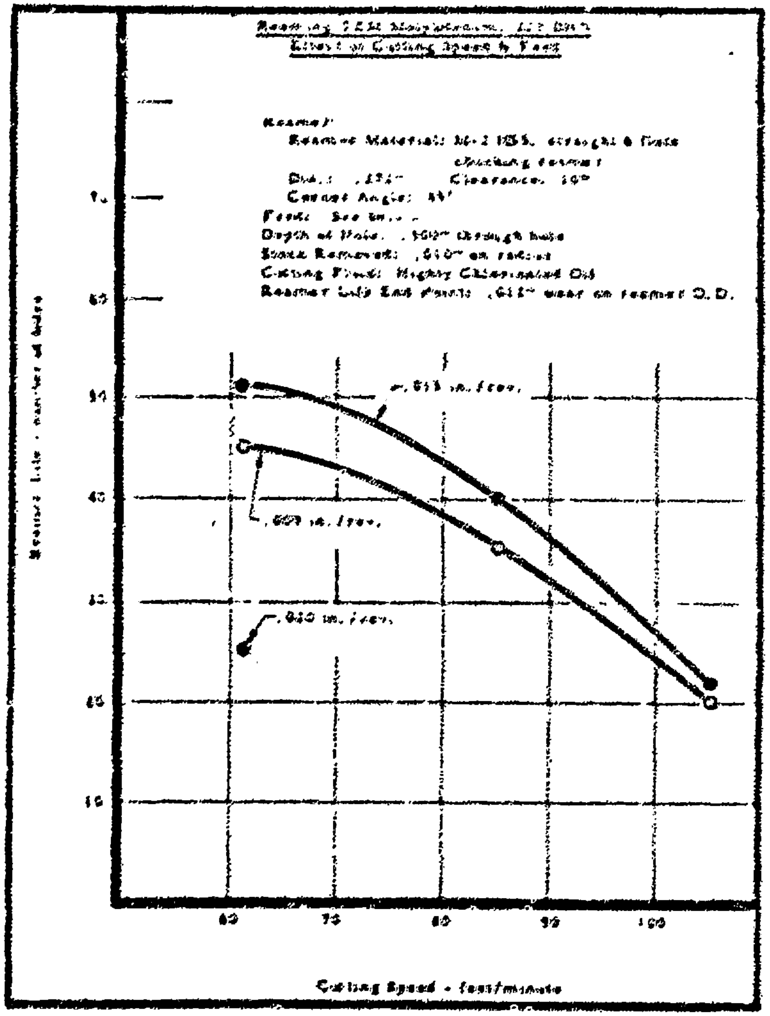

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Figure 110

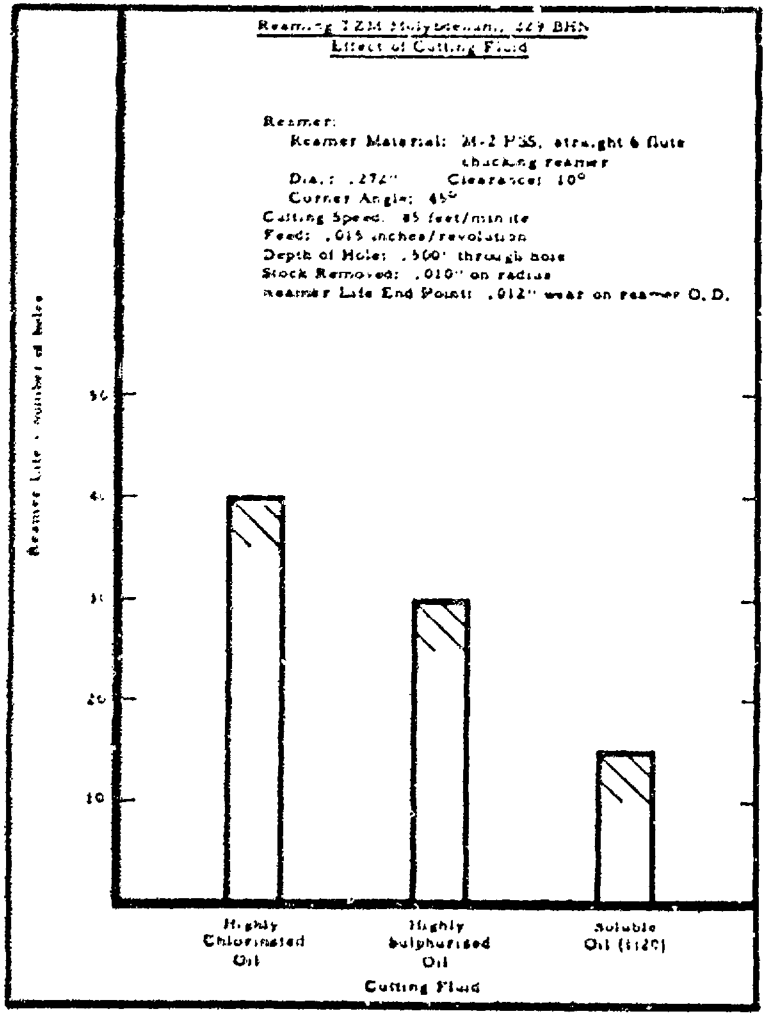

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Figure 111

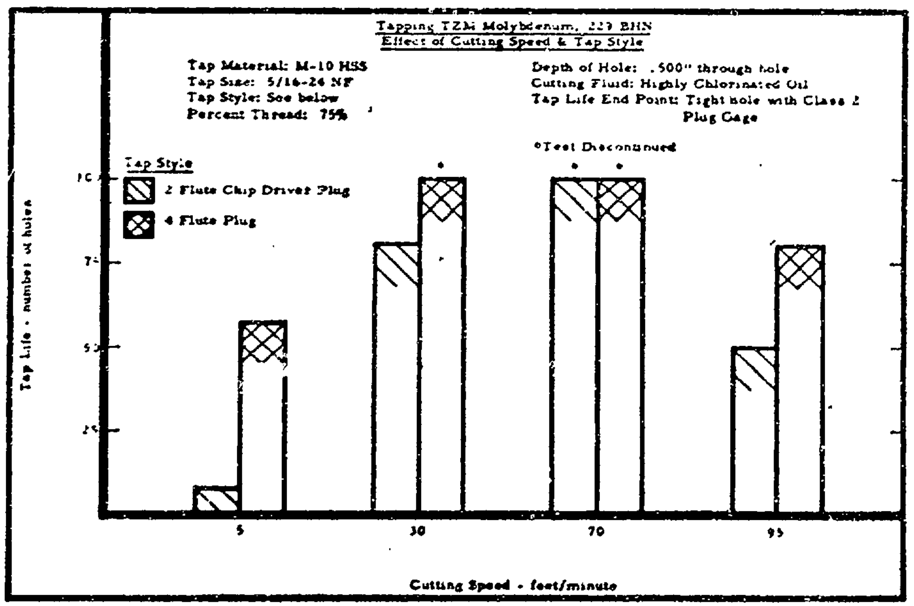

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Figure 112

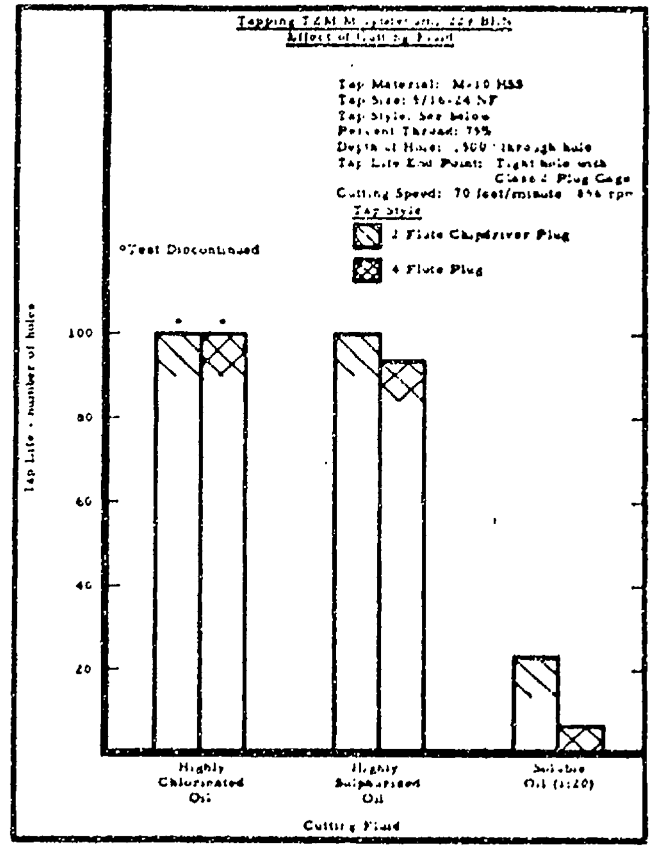

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Figure 111

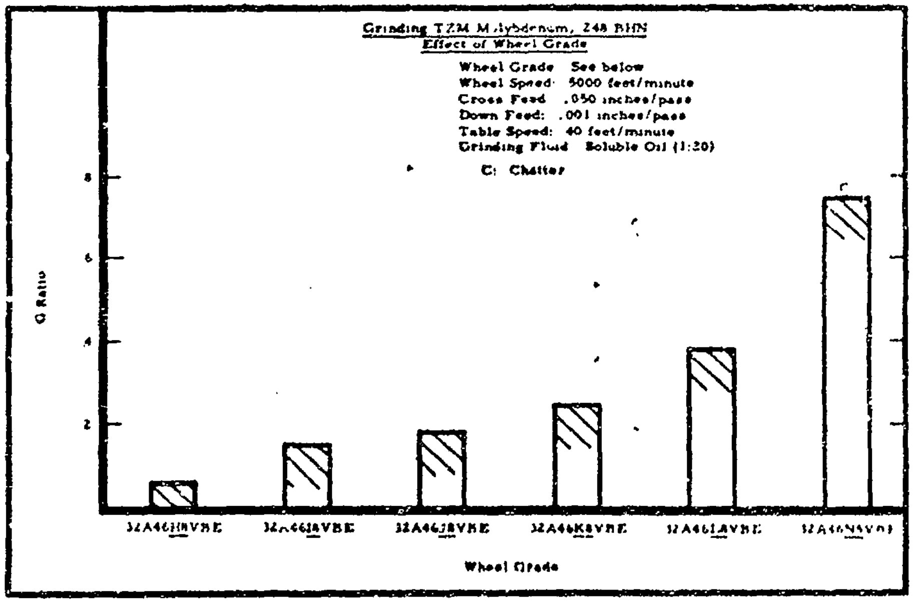

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Figure 114

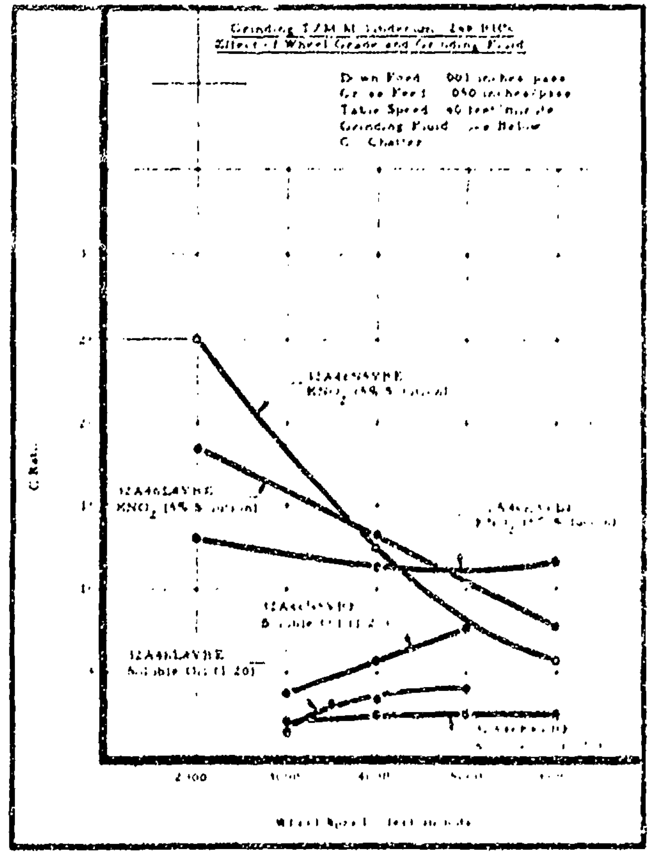

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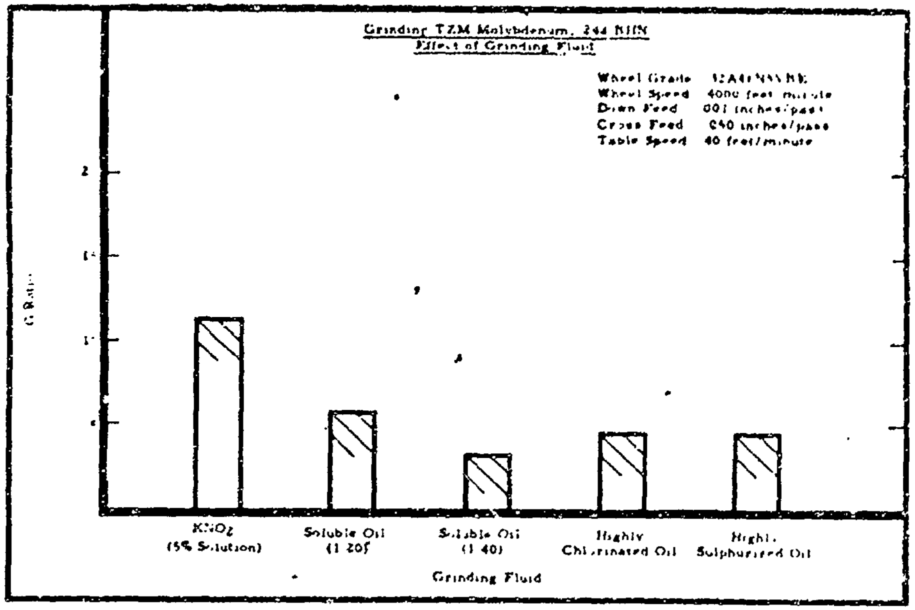
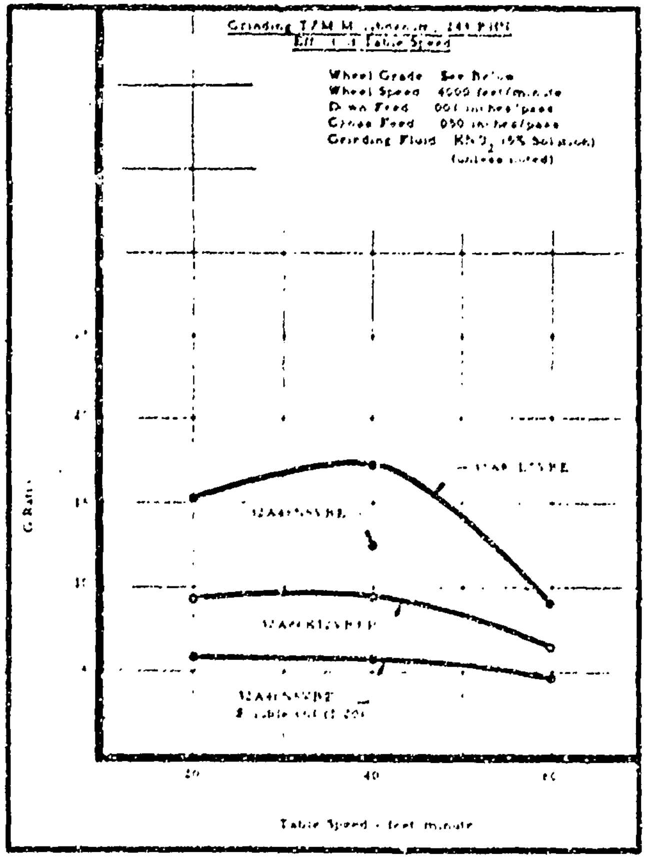
Figure 115



See Text, page 82

Figure 116



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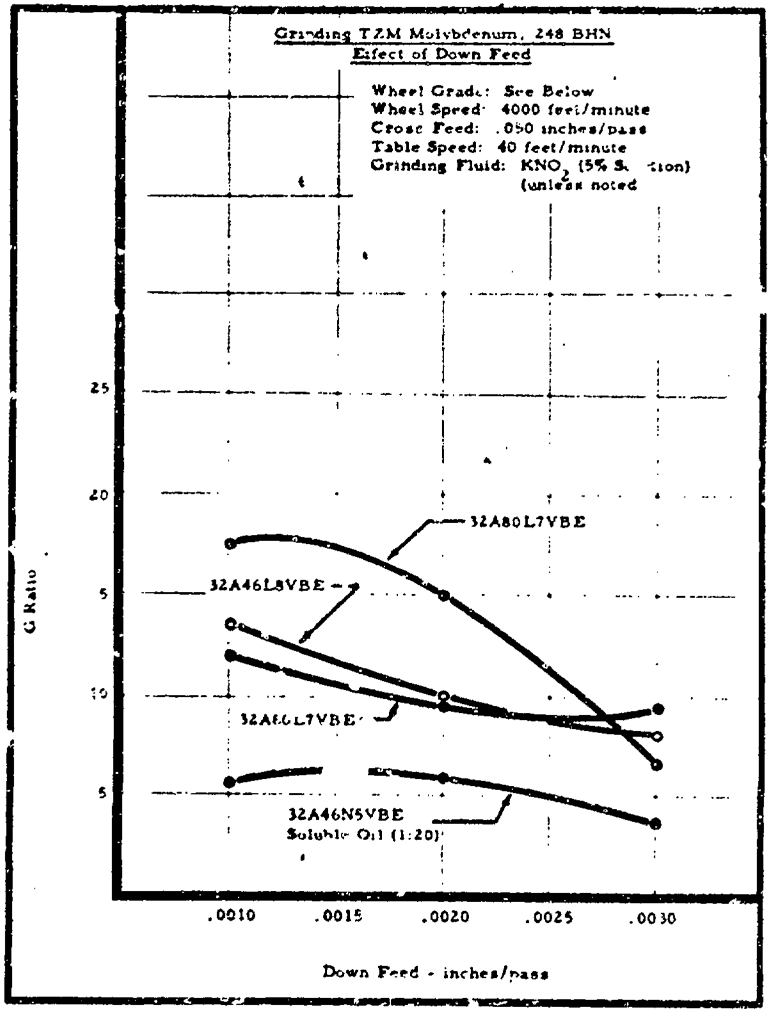

See Text page 82

Figure 11a

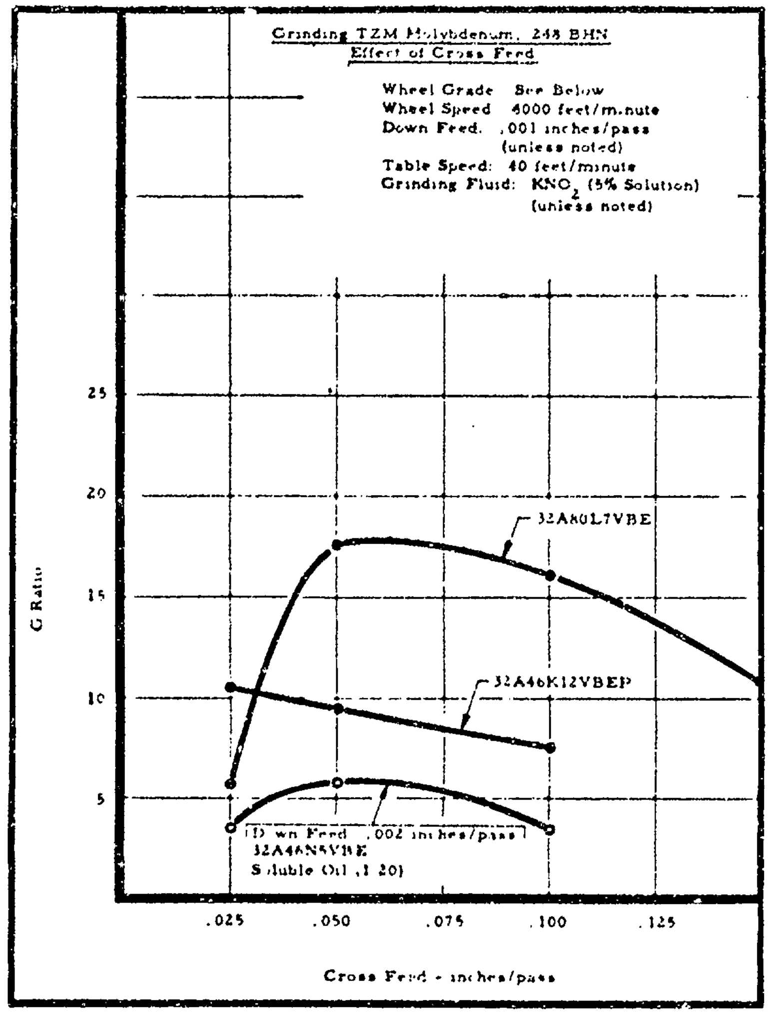

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Figure 11b

Recommendations for Machining Molybdenum-0.5% Titanium Alloy

The Mo-0.5 Ti alloy machines very much the same as the TZM alloy discussed previously. This alloy also chips out quite easily and care should be taken to prevent its occurrence. General recommendations for machining the molybdenum-0.5% titanium alloy are given in Table 7, page 107.

Turning

The tool life curves shown in Figure 120, page 108, indicate that side rake is very important in turning Mo-0.5% Ti with carbide tools. For a feed of .009 in./rev. and a depth of cut of .030", a 24 minute tool life was obtained at a cutting speed of 350 feet/minute using a grade 883 (C-2) carbide tool with a positive side rake of 20°. Using a positive side rake of 6°, cutting speed had to be reduced to 175 feet/minute to obtain any appreciable tool life.

Figure 121, page 108, presents tool life curves obtained in carbide turning the Mo-0.5% Ti alloy with a soluble oil cutting fluid and also cutting dry. The curves show that for equivalent tool life cutting speed can be increased by approximately 10% when turning with a soluble oil, as compared with turning dry.

The effect of depth of cut is shown in Figure 122, page 109, when turning Mo-0.5% titanium, using a feed of .009 in./rev. The tool life curves show that for an equivalent tool life, cutting speed for a depth of cut of .060" had to be decreased 15%, compared with taking a .030" depth of cut. However, the higher production rate with the depth of cut of .060" more than offsets the 15% decrease in cutting speed.

Face Milling

Tool life data for face milling with carbide and high speed steel cutters are shown in Figures 123 through 131, pages 109 through 113.

The effect of cutter geometry on tool life is presented in Figure 123, page 109. The data shows that maximum tool life was obtained with a cutter ground with a 0° axial rake and 0° radial rake with a 45° corner angle. This combination of axial rake, radial rake and corner angle produced a resultant rake angle of 0° and an angle of inclination of 0°. Significantly lower values of tool life were obtained with cutters having various combinations of positive and negative resultant rakes and angles of inclination.

Figure 124, page 110, shows the effect of feed for both the 0° axial rake, 0° radial rake cutter and a cutter ground with a 10° axial rake and 20° radial rake. The data clearly indicates that both tool life and cutting speed can be increased when using the 0° geometry cutter, as compared to using the other cutter

geometry. Figure 124 also shows that when the feed was increased from .005 in./tooth to .010 in./tooth, the cutting speed had to be reduced about 15% to maintain an equivalent tool life.

Figure 125, page 110, shows the effect of feed for depths of cut of .030" and .060" in face milling. When taking a .030" depth of cut at a cutting speed of 286 feet/minute, tool life decreased from 120 inches work travel per tooth at a feed of .002 in./tooth to 90 inches work travel per tooth at a feed of .010 in. per tooth. However, for the .060" depth of cut at a lower cutting speed of 230 feet/minute, tool life decreased very sharply from 140+ inches work travel per tooth to ten inches per tooth when the feed was increased from .002 inches per tooth to .010 in./tooth. These results indicate that lighter feeds are required when the depth of cut is increased.

The effect of carbide grade is shown in Figure 126, page 111. The C-2 grade 883 carbide was far superior to the C-1, C-3 or C-7 grades tested at the same conditions. Using a feed of .005 in./tooth, a cutting speed of 230 feet/minute and a .060" depth of cut, the tool life for the grade 883 C-2 carbide was 120 inches work travel per tooth. All other grades failed from localized breakdown at less than 30 inches per tooth work travel.

Figure 127, page 111, also shows the importance of using a cutting fluid when face milling the Mo-0.5% Ti alloy with carbide cutters. Only ten inches of work travel per tooth was obtained with the C-2 grade of carbide without the use of a soluble oil cutting fluid, before severe chipping occurred; while with a flood of soluble oil almost 60 inches of work travel per tooth resulted with no chipping.

The effect of cutting speed for .030" and .060" depths of cut is shown in Figure 128, page 112. Using a feed of .005 in./tooth, a tool life of 110 inches work travel was obtained for the .030" depth of cut at a cutting speed of 290 feet/min. To obtain the same tool life with a .060" depth of cut, the cutting speed had to be reduced to 230 feet/minute. Tool life decreased more rapidly with increased cutting speed for the .060" depth of cut than for the .030" depth of cut.

Figure 129, page 112, shows the effect of tool geometry and cutting fluid in high speed steel face milling. At a cutting speed of 100 feet/minute, using a .010 in. per tooth feed and a depth of cut of .030", both a soluble oil and a chemical solution provided equal tool life of 40 inches work travel with a cutter having axial and radial rakes of 10°. Using the soluble oil cutting fluid, a tool life of 55 inches work travel was obtained for a cutter with 0° axial and radial rakes.

The effect of feed in face milling with high speed steel cutters is presented in Figure 130, page 113. Tool life increased as the feed was changed from .005 to .015 in./tooth. However, at a feed of .015 in./tooth, localized breakdown occurred before a uniform wearland of .016" could be obtained. For this reason, feeds greater than .010 in./tooth are not recommended.

Face Milling (continued)

For a .060" depth of cut, a tool life of 50 to 70 inches work travel was obtained at cutting speeds between 80 and 100 feet/minute using a .010 in./tooth feed and a soluble oil cutting fluid. For a .030" depth of cut, equal tool life was obtained at cutting speeds 10 to 15% higher. No advantage was found for the cobalt type T-15 tool material over the T-1 material. At a cutting speed of 100 feet/minute and .060" depth of cut, approximately 45 inches work travel was obtained with both types. See Figure 131, page 113.

Drilling

The initial tests in drilling the Mo-0.5% Ti alloy were made to determine the effect of drill material, and the results are presented in Figure 132, page 114. The tests were conducted at a cutting speed of 120 feet/minute, a feed of .005 in./rev., using a highly chlorinated oil as the cutting fluid, and .128" (No. 30) diameter drills made of three different high speed steels. The results showed that drill life was essentially the same for the M-33, M-7 and M-1 high speed steel drills tested.

Figure 133, page 114, shows the effect of drill geometry in drilling this alloy using M-1 high speed steel drills at a cutting speed of 150 feet/minute, a feed of .005 in./rev. and a highly chlorinated oil as the cutting fluid. Best drill life results were obtained using a drill with a double point angle of 118° at the point and a 90° angle on the corner. The tests also showed that drill life for a drill with a 118° point angle and a 7° clearance was appreciably better than a drill with a 12° clearance and the same point angle.

Figure 134, page 115, shows the effect of cutting fluid in drilling Mo-0.5% Ti using M-1 high speed steel drills at a cutting speed of 150 feet/minute and a feed of .005 in./rev. Best drill life of 35 holes was obtained using a highly chlorinated oil. Twenty-two holes were obtained using a soluble oil diluted 20 to 1; 19 holes with a chemical solution diluted 20 to 1; and only six holes with a highly sulphurized oil diluted 1 to 1 with light machine oil.

Figure 135, page 115, shows the effect of cutting speed and feed in drilling with Type M-1 high speed steel drills. The tool life curves indicate that drill life decreases rapidly with increasing cutting speeds for both feeds of .005 in./rev. and .009 in./rev. Good drill life was obtained at a cutting speed of 100 feet per minute for both feeds used in the tests.

Reaming

The tool life end point used in the reaming tests reported was .010" wearland on the chamfer of the reamer. The hole size was checked at frequent intervals and at no time during the tests did the size of the hole exceed .001" under the nominal size.

Reaming (continued)

Tool life data for right hand helix, left hand helix, and straight fluted reamers is shown in Figure 136, page 116. No appreciable difference in tool life was found for these three reamer styles. For a .010" depth of cut, using a cutting speed of 64 feet/minute, a feed of .009 in./rev. and a highly chlorinated oil cutting fluid, reamer life varied between 23 and 30 holes for the three reamer styles. The right hand spiral reamer style was used for all subsequent tests.

The effect of feed in reaming is shown in Figure 137, page 116. At a cutting speed of 84 feet/minute, reamer life increased with increasing feed from 25 holes for a .007 in./rev. feed to 60 holes for a .020 in./rev. feed. While maximum tool life was obtained using the high feed, better hole surface finish was obtained at lower feeds.

The effect of cutting fluid is shown in Figure 138, page 117, when reaming Mo-0.5% Ti with high speed steel reamers. Both a highly chlorinated oil and a highly sulphurized oil diluted 1 to 1 with light machine oil produced equally good results. However, only 25 holes could be reamed using a soluble oil (20:1), as compared to approximately 60 holes for the other two cutting fluids.

Tapping

Figure 139, page 117, shows the effect of cutting fluid and tap design in tapping Mo-0.5% Ti alloy using 1/4-28 NF taps made of M-10 high speed steel at a cutting speed of 56 feet/minute. A tap life of over 100 holes can be obtained with 4 flute plug taps or 2 flute chip driver taps, providing a highly chlorinated oil is used. When using a highly sulphurized oil, only a surface treated 2 flute chip driver tap could be used to obtain a tap life of over 100 holes. It is significant to note that with a 4 flute plug tap no holes could be tapped using a highly sulphurized oil, while tap life for the same tap design was over 100 holes when a highly chlorinated oil was used as the cutting fluid. Poor tap life was also obtained when using soluble oil for the two tap designs tested.

The effect of cutting speed in tapping Mo-0.5% Ti using 1/4-28 NF 2 flute chip driver taps is shown in Figure 140, page 118. Tap life was 70 holes using a cutting speed of 31 feet/minute, while over 100 holes were tapped at 56 feet per minute with the tap still cutting when the test was discontinued.

The data in Figure 141, page 118, compares results in tapping coarse and fine threads of two designs: 2 flute chip driver types, and 4 flute plug types. The cutting speed used was 56 feet/minute for all tests, and all taps were made of M-10 high speed steel. The tapped holes for the 1/4-28 NF taps (fine thread) were 80% thread, while the tapped holes for the 1/4-20 NC (Coarse thread) were 75% thread. Over 100 holes were obtained with both the 1/4-28 NF 2 flute chip driver tap and the 1/4-28 NF 4 flute plug tap when the tests were discontinued. Likewise, over 100 holes were obtained with the 1/4-20 NC 2 flute chip driver tap when the test was discontinued. However, it was not possible to tap a single hole with the 1/4-20 NC 4 flute plug tap.

Surface Grinding

In grinding the Mo-0.5 Ti alloy, surface finish measurements ranged from 10 to 40 microinches, depending upon the grinding condition used. This alloy loads the wheel up very rapidly and frequent wheel dressing is necessary. A chatter condition will occur if a loaded wheel is used, and the possibility of developing surface cracks is increased. Results of the grinding studies for molybdenum-0.5% titanium alloy are shown in Figures 142 through 147, pages 119 through 121.

Figure 142, page 119, shows the effect of wheel speed on the grinding ratio. A maximum G ratio of 3.2 was obtained for a wheel speed of 4000 feet/minute. G ratio decreased for both higher and lower speeds. A wheel speed of 4000 feet/minute was used for all subsequent tests.

The effect of table speed is shown in Figure 143, page 119. G ratio increased with decreasing table speeds between 60 and 20 feet/minute. The maximum G ratio of 5.0 was obtained at 20 feet/minute table speed. However, the increase in G ratio at 20 feet/minute table speed was not significant enough to justify the low table speed. A table speed of 40 feet/minute was used for all subsequent tests.

Down feeds were evaluated next. The effect of down feed on G ratio is shown in Figure 144, page 120. The maximum G ratio of 5.2 was obtained for a down feed of .0005 in./pass. G ratio decreased with increasing down feed to a value of 1.6 for a .002 in./pass down feed. A down feed of .001 in./pass was used for succeeding tests.

Figure 145, page 120, shows the effect of cross feed on G ratio. The maximum G ratio of 4.7 was obtained at the low cross feed of .025 in./pass. G ratio decreased with increasing cross feed. The decrease was not significant enough to warrant the use of the .025 in./pass cross feed; therefore, a .050 in./pass cross feed was used for succeeding tests.

The effect of wheel grade is shown in Figure 146, page 121. A G ratio of about 3.2 was obtained for both the 32A46H8VBE and 32A46J8VBE wheels. G ratio increased to 4.4 when using a 32A46L8VBE wheel grade. However, this wheel had a tendency to load and produce chatter marks on the workpiece.

Figure 147, page 121, shows the effect of grinding fluids. A soluble oil diluted 40 to 1 was slightly better than the chemical solution diluted 40 to 1 or the highly chlorinated and highly sulphurized oils used.

TABLE 7

RECOMMENDED CUTTING CONDITIONS FOR MACHINING AND GRINDING

Mo - 0.5 Ti MOLYBDENUM ALLOY

Nominal Chemical Composition, Percent

Ti	C	Mo
0.45	.020	Bal.

Operation	Tool Material	Tool Geometry	Tool Used for Tests	Depth of Cut inches	Width of Cut inches	Feed	Cutting Speed ft./min	Tool Life	Wear-land Inches	Cutting Fluid
Turning	C-2 Carbide	SR: 20° SCEA: 15° BR: 0° ECEA: 15° Relief: 7°	5/8" square brazed tip tool bit	.060	---	.009 in/rev	300	25 min.	.010	Soluble Oil (20:1)
Face Milling	C-2 Carbide	AR: 0° ECEA: 10° RR: 0° CI: 15° CA: 45°	4" diameter single tooth face mill	.060	2	.005 in/tooth	225	120 inches	.012	Soluble Oil (20:1)
Drilling	M-1 HSS	2 flute, 118° plain point 7° clearance	.193" diameter drill 2-1/4" long	.500 thru hole	---	.005 in/rev	100	100 holes	.012	Highly Chlorinated Oil
Reaming	M-2 HSS	10° RH Helix 45° CA 10° Clearance	6 flute straight shank chucking reamer	.500 thru hole	.010 depth on hole radius	.015 in/rev	85	45 holes	.010	Highly Chlorinated Oil
Tapping	M-10 HSS	2 flute chip driver tap 80% thread	1/4-28 NF	.500 thru hole	---	---	56	100+ holes	Tap still cutting	Highly Chlorinated Oil

SURFACE GRINDING

Wheel Grade	Grinding Fluid	Wheel Speed feet/minute	Table Speed feet/minute	Down Feed inches/pass	Cross Feed inches/pass	G Ratio
32A46J8VBE	Soluble Oil (40:1)	4000	40	.001	.050	3.3

See Text, page 102

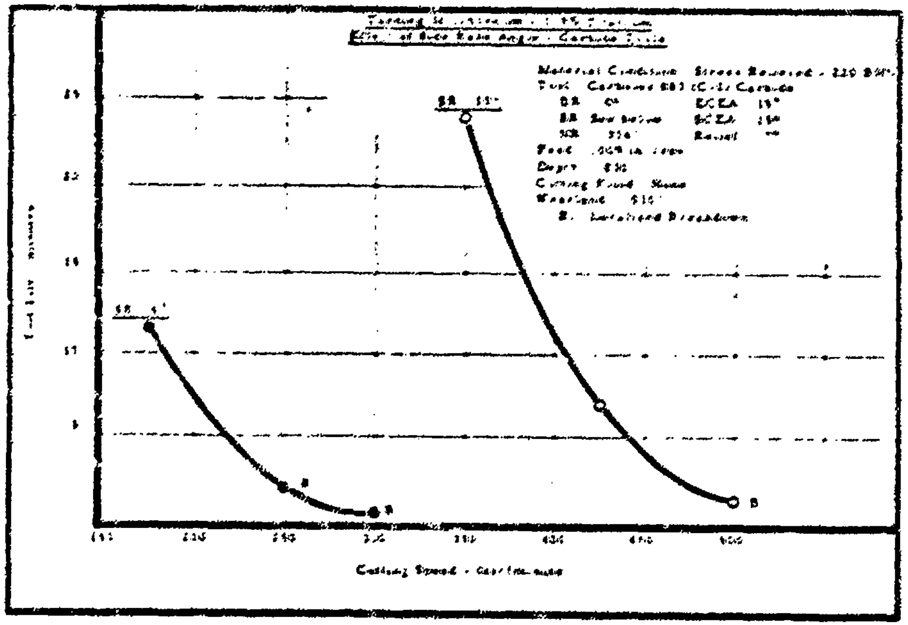

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Figure 120

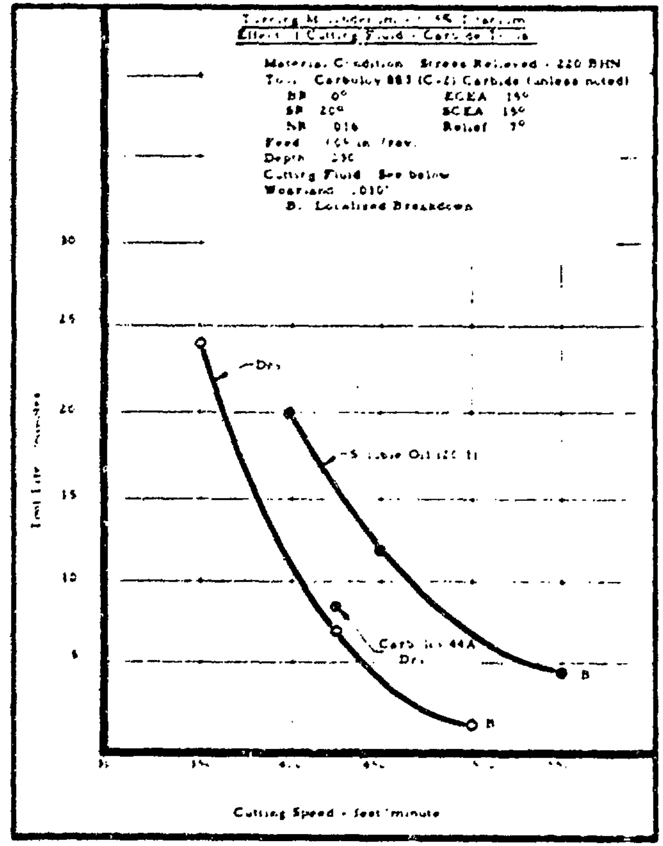

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Figure 121

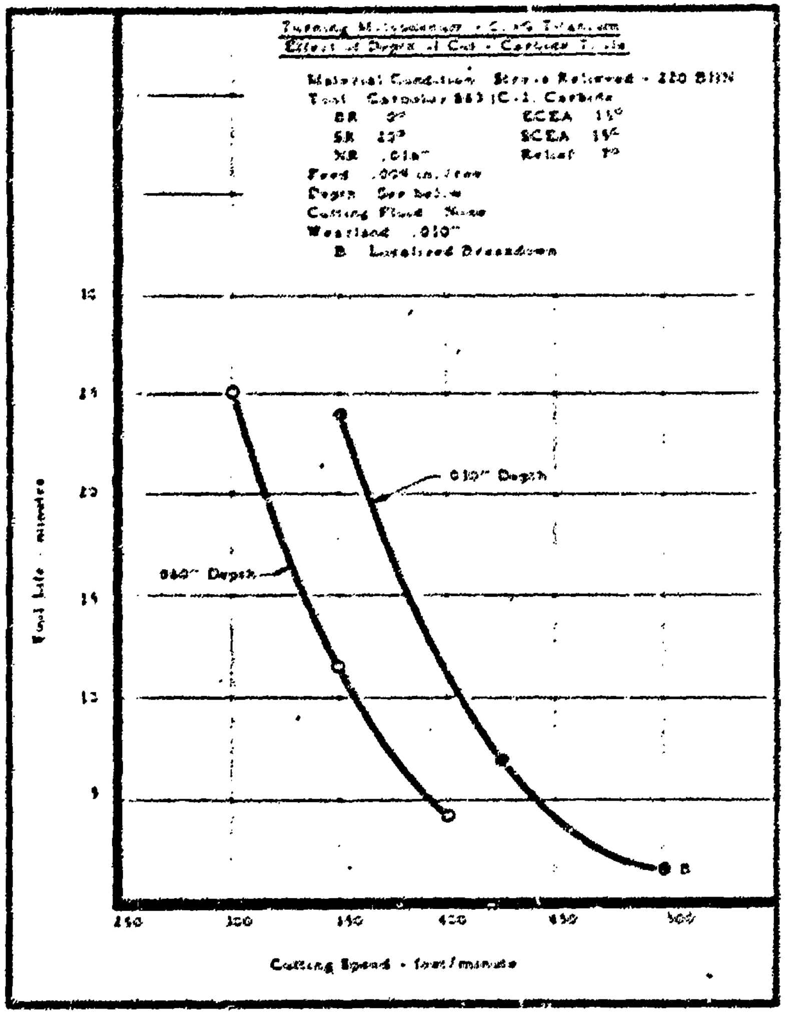

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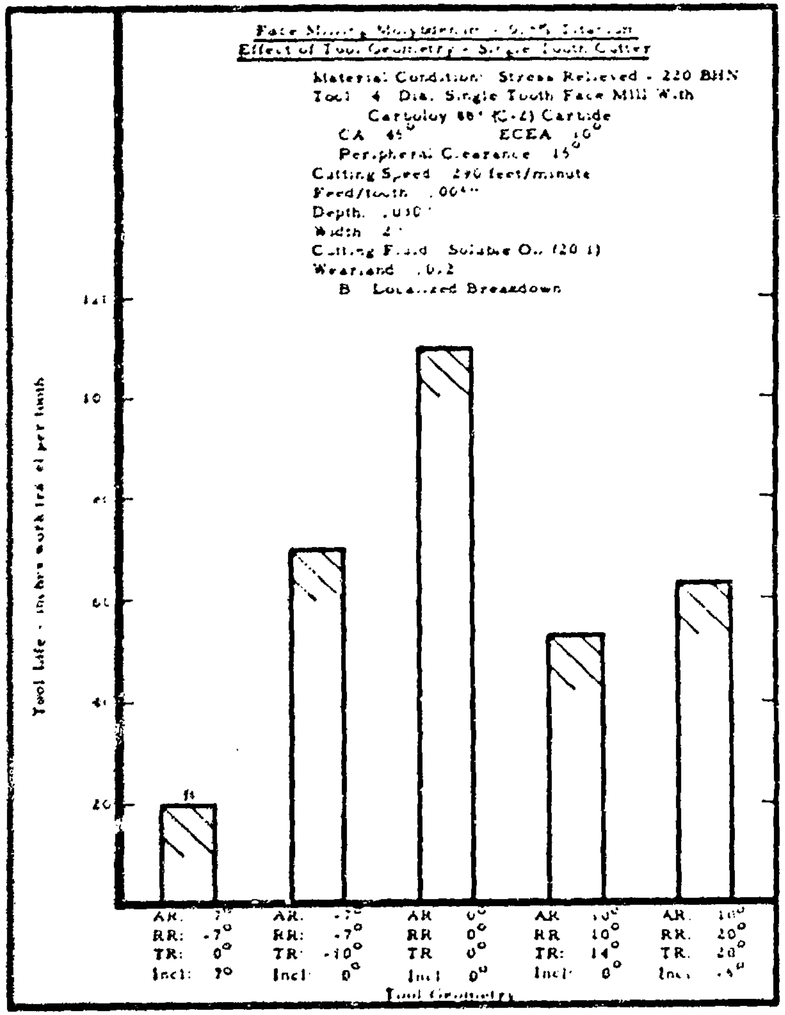
Figure 122



See Text, page 104

Figure 123

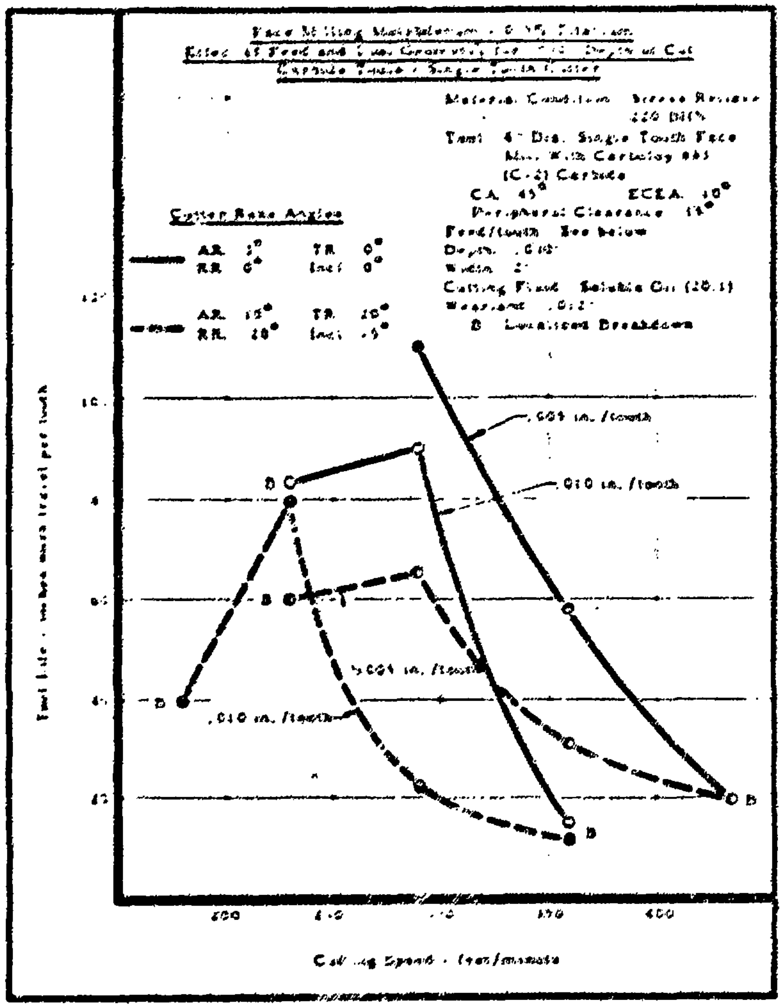


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Figure 124

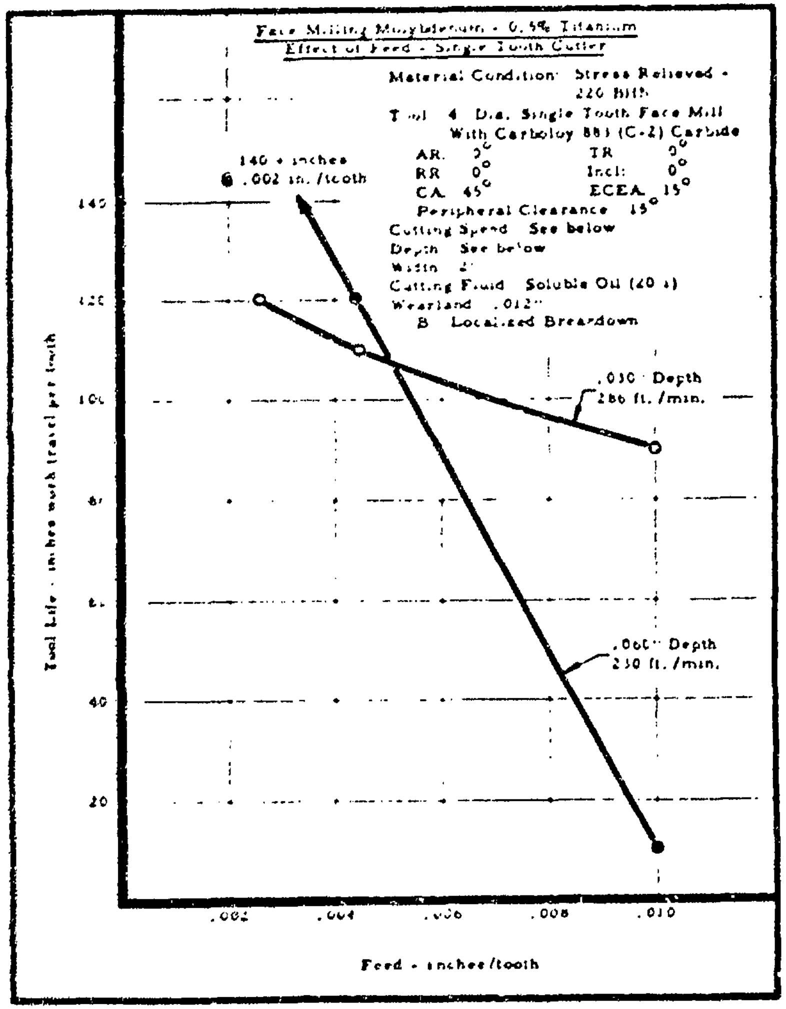

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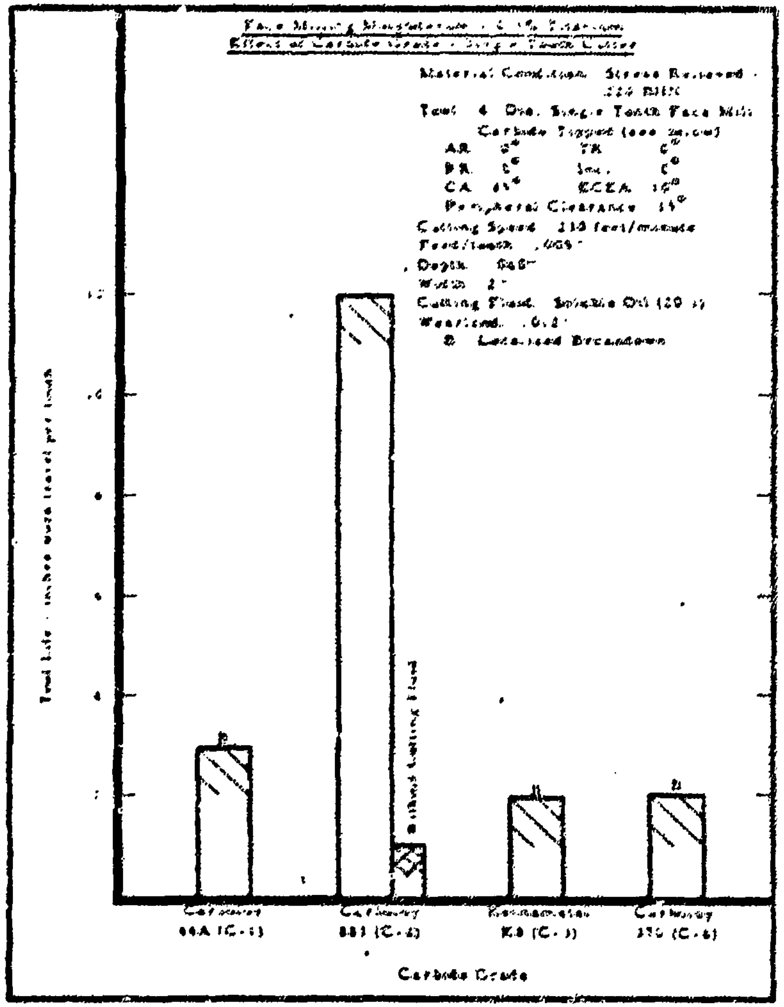
Figure 125



See Text, page 103

Figure 126

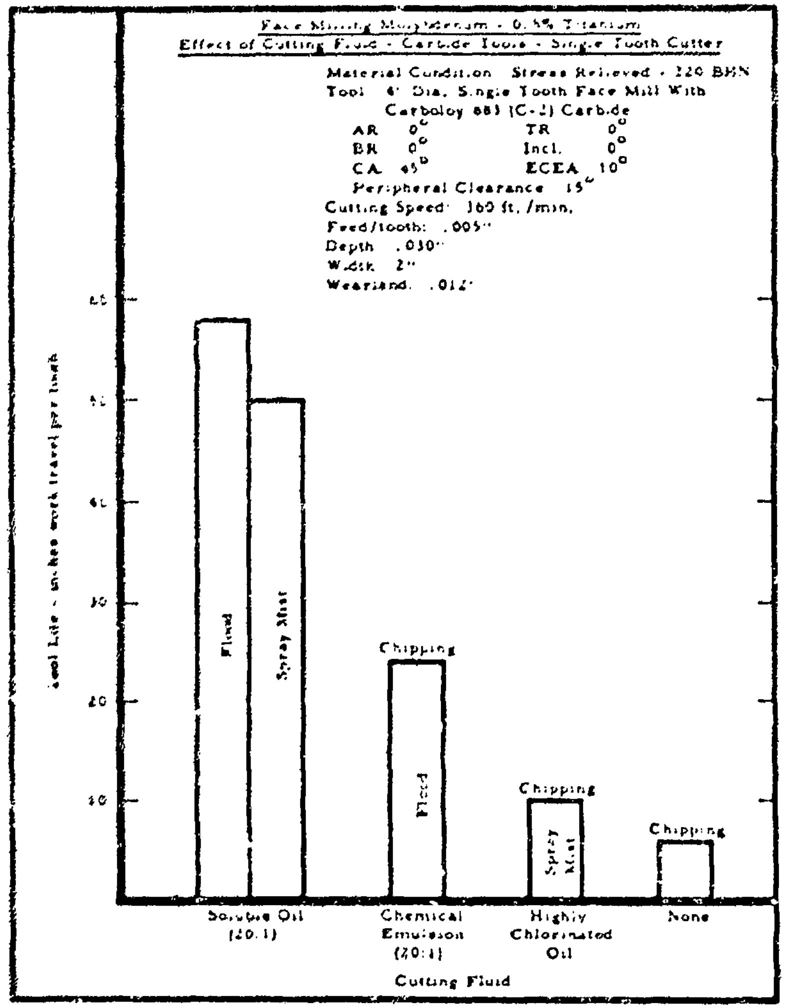


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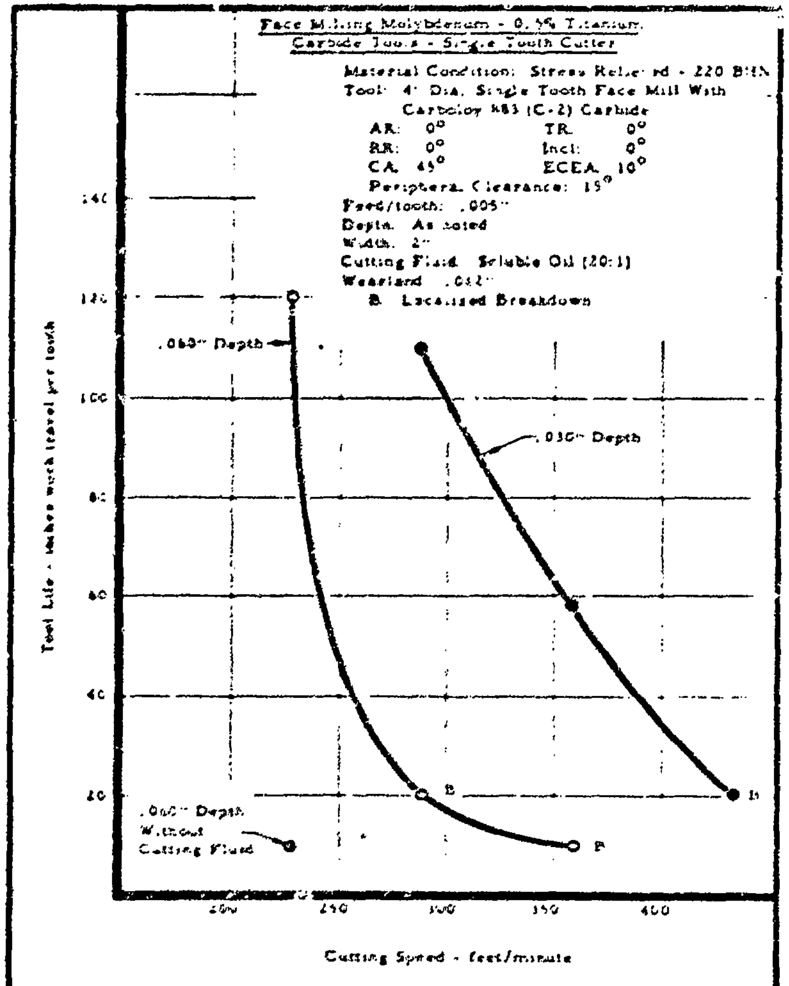
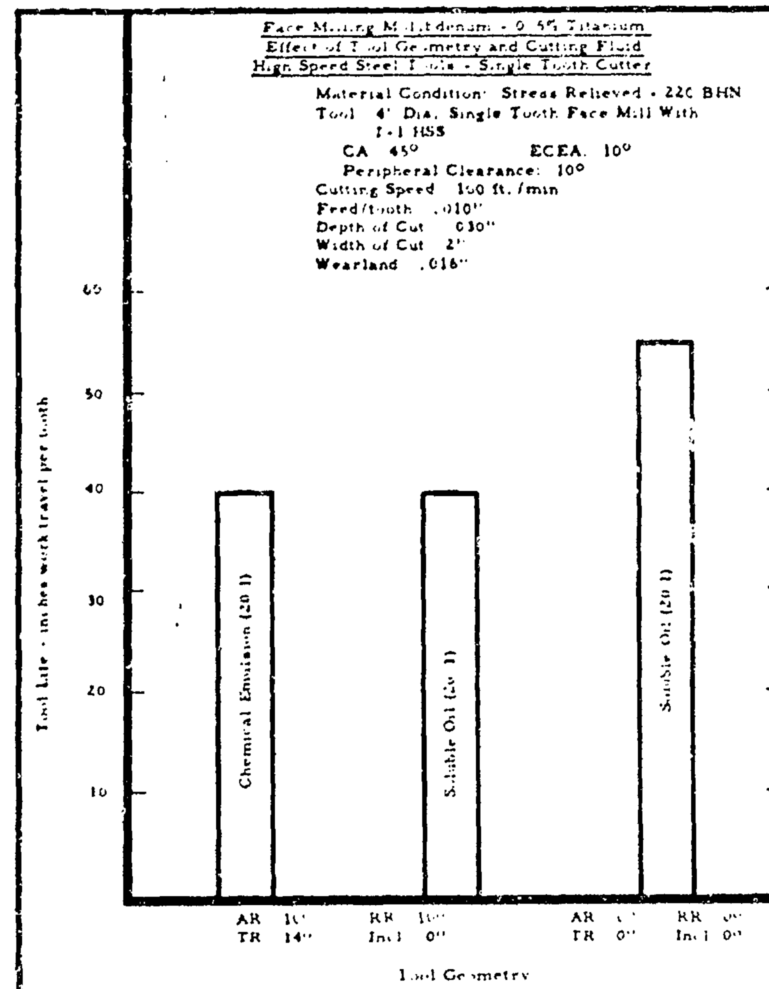
Figure 127



See Text, page 103

Figure 128



See Text, page 103

Figure 129

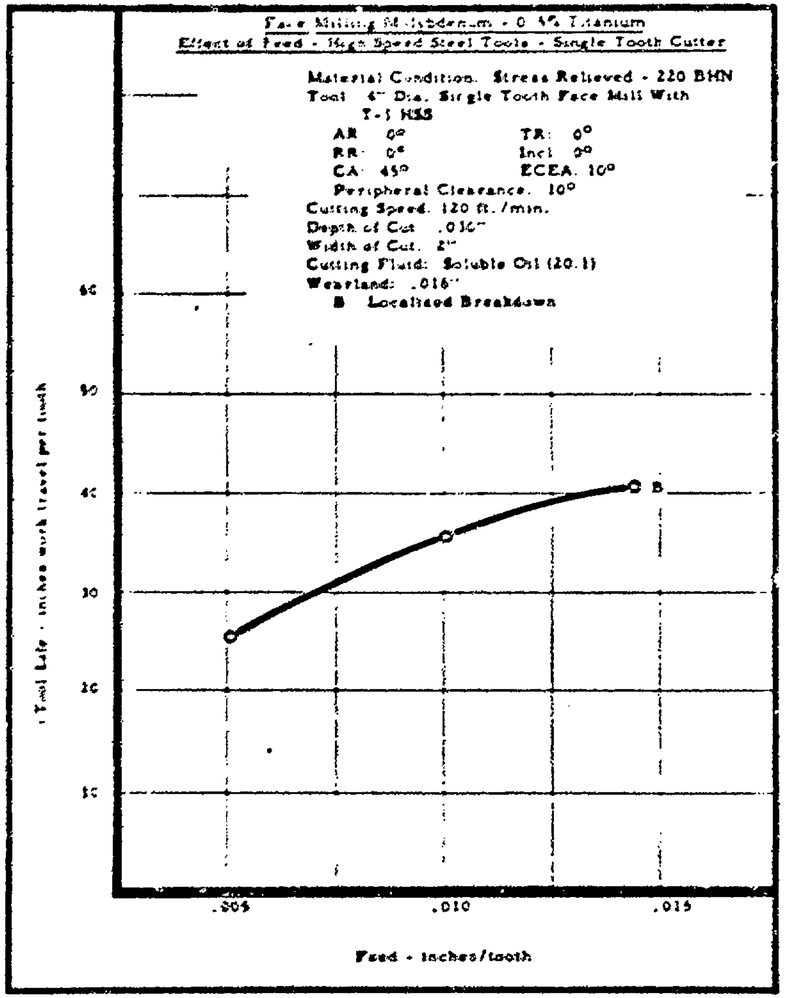


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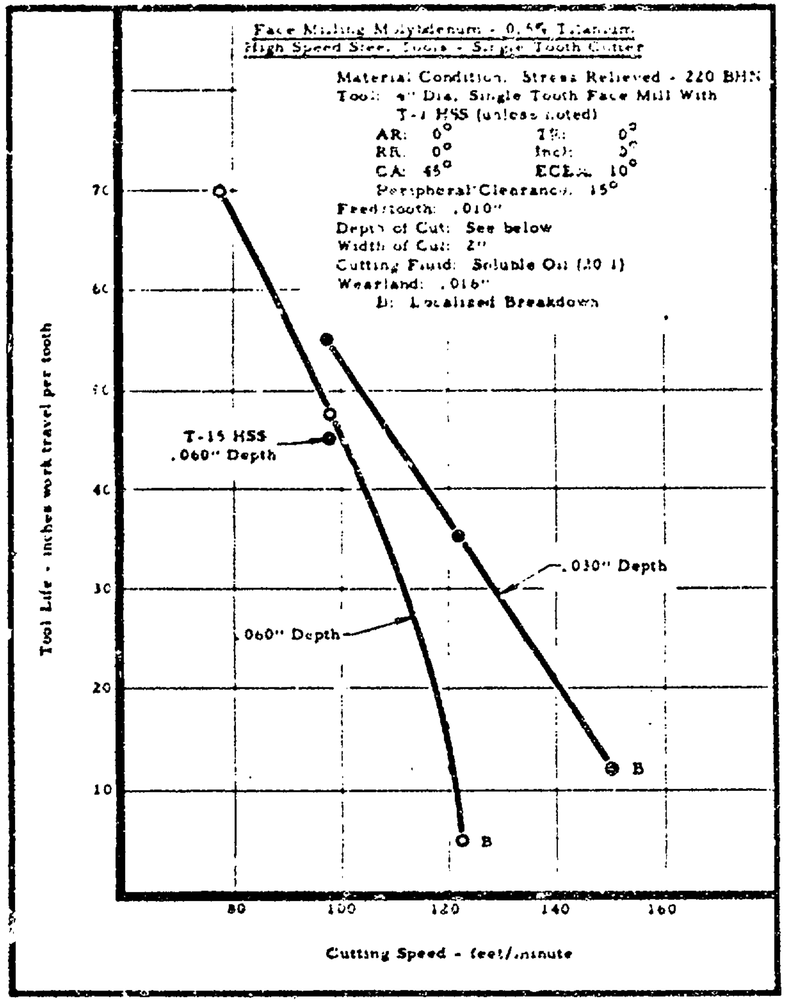
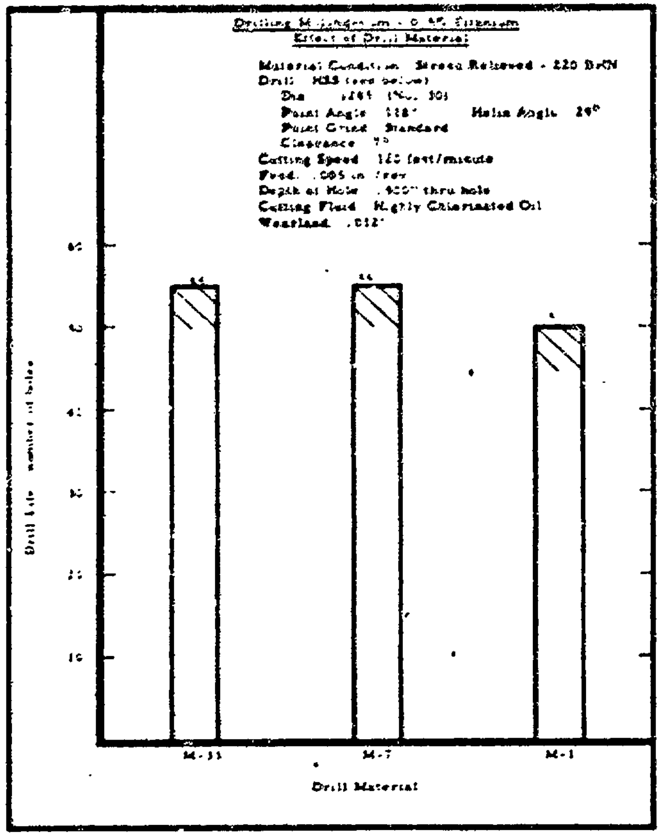
Figure 130



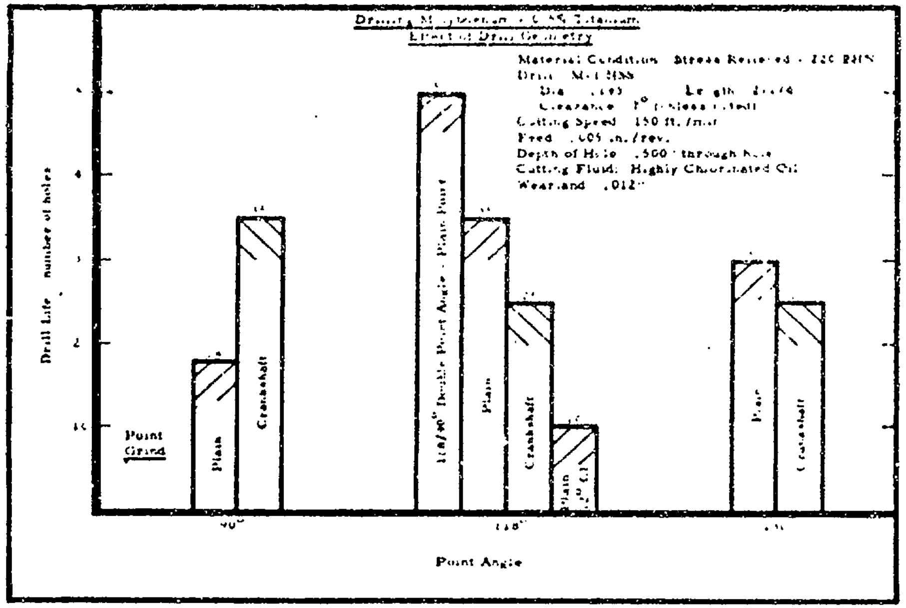
See Text, page 104

Figure 131



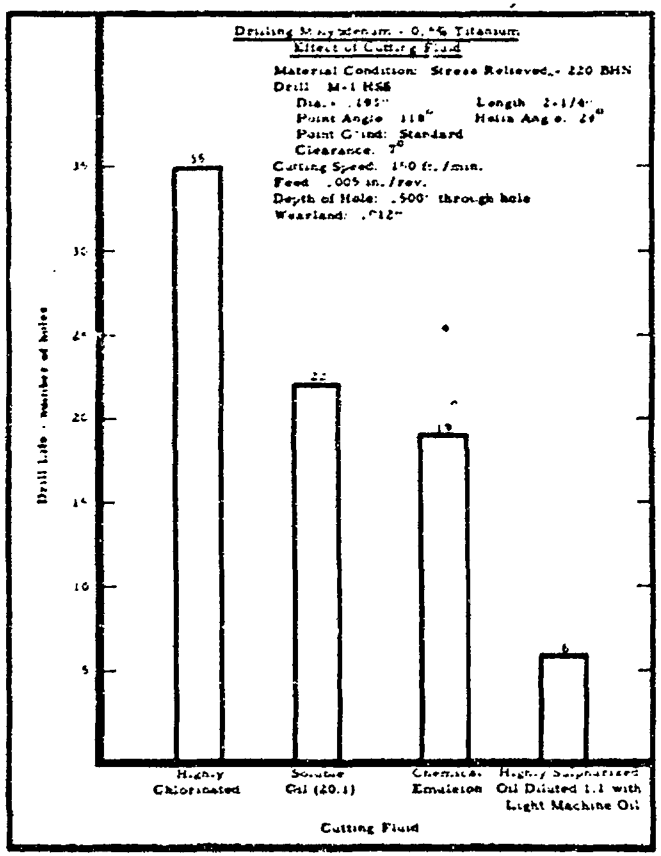
See Text, page 104

Figure 132



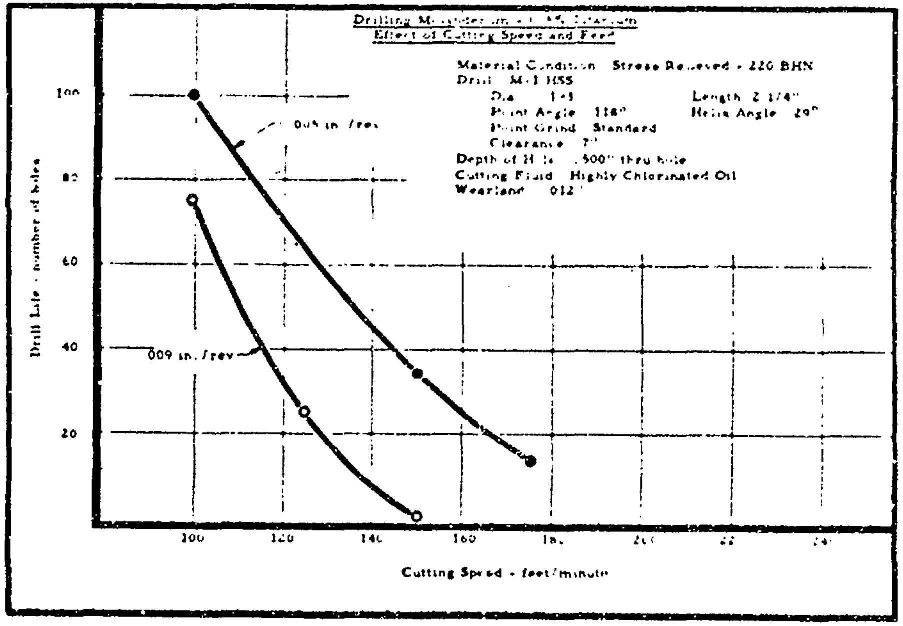
See Text, page 104

Figure 133



See Text, page 104

Figure 134



See Text, page 104

Figure 135

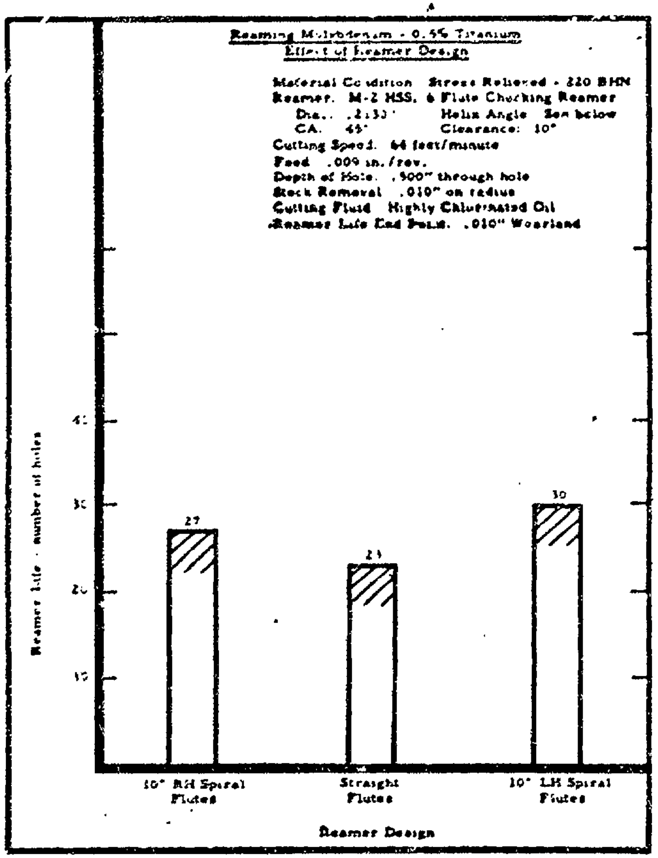


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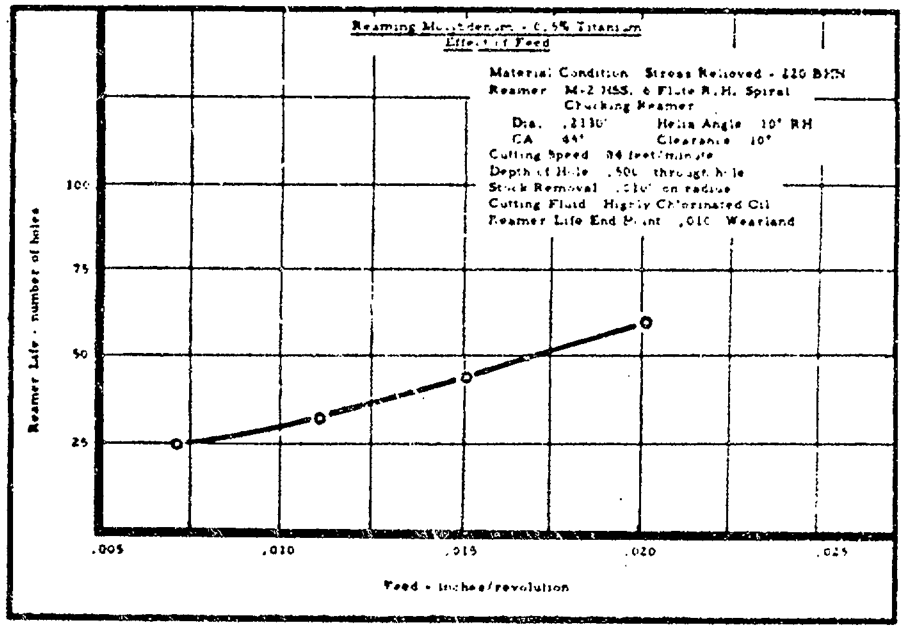
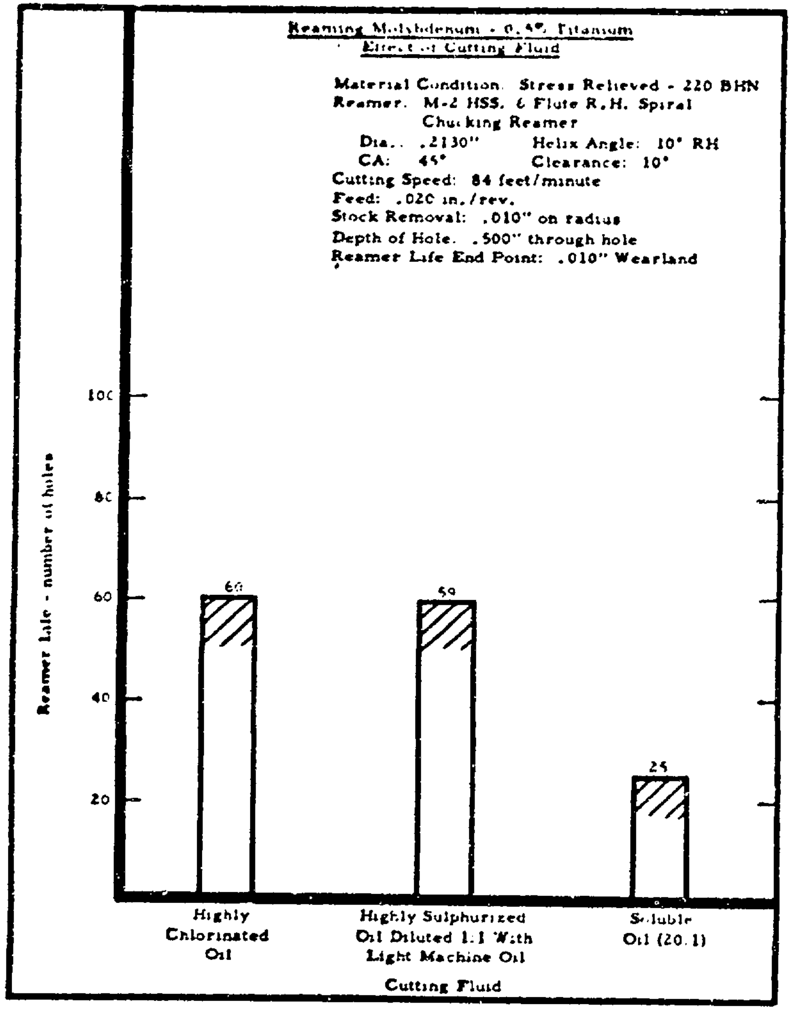
Figure 136



See Text, page 105

Figure 137



See Text, page 109

Figure 138

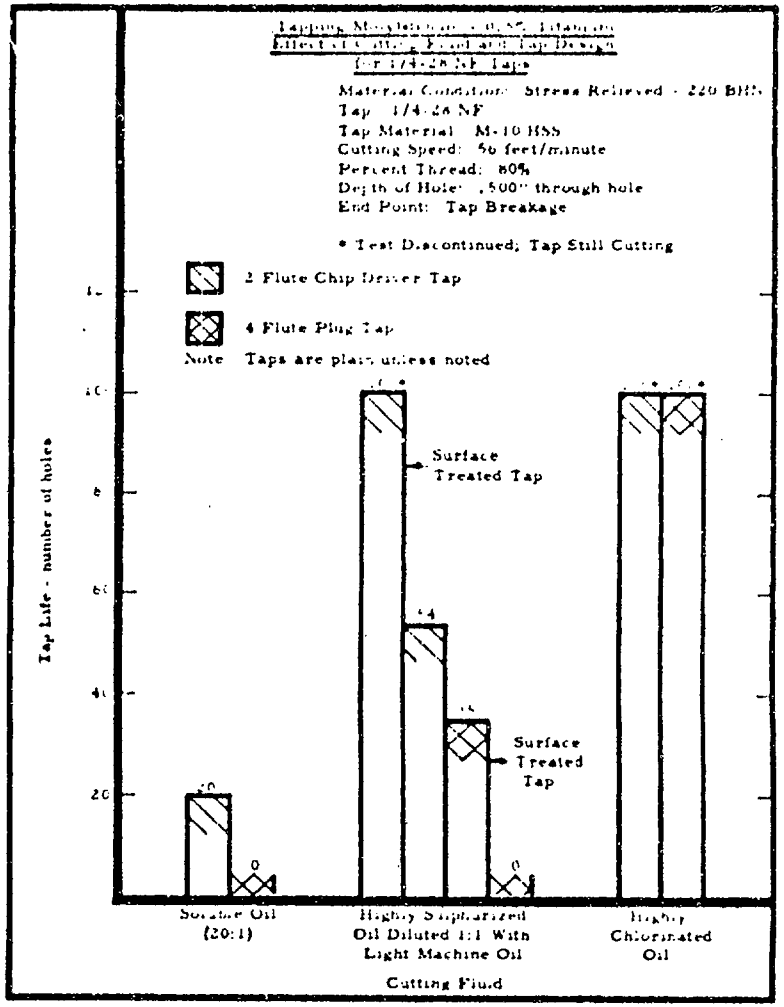


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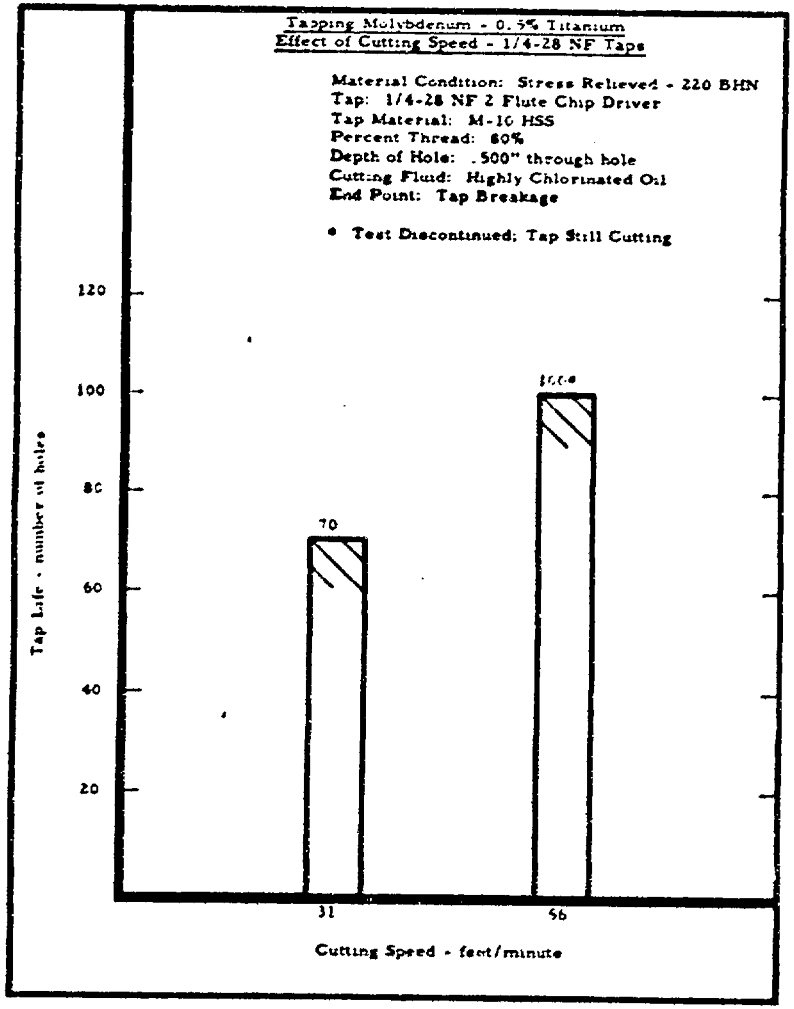
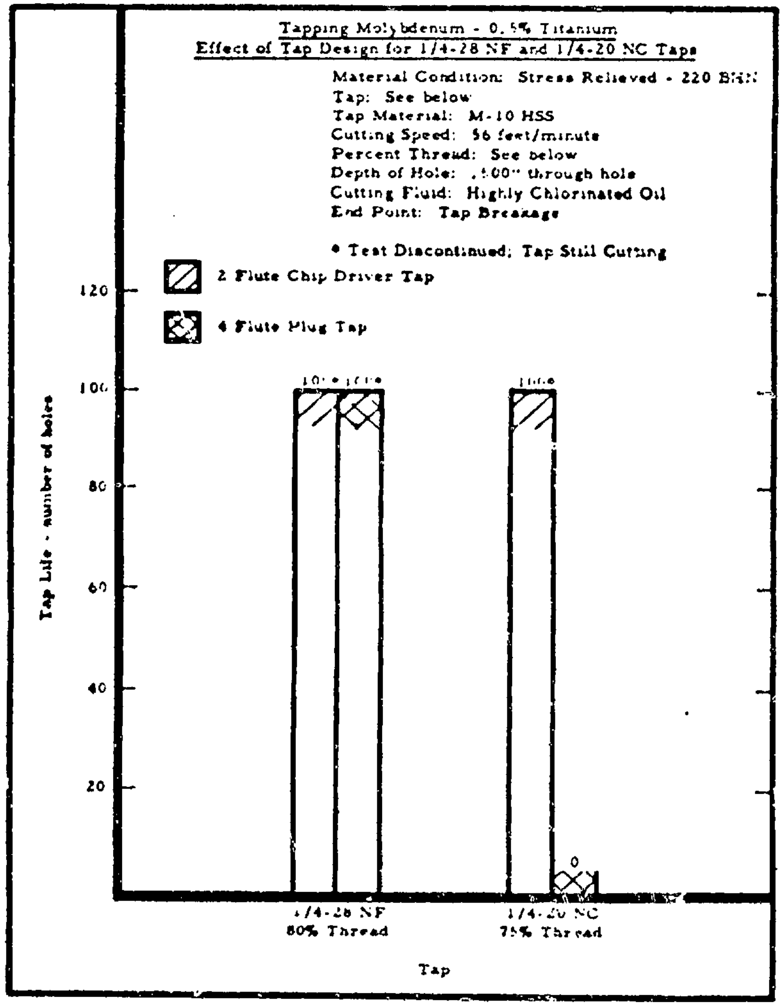
Figure 139



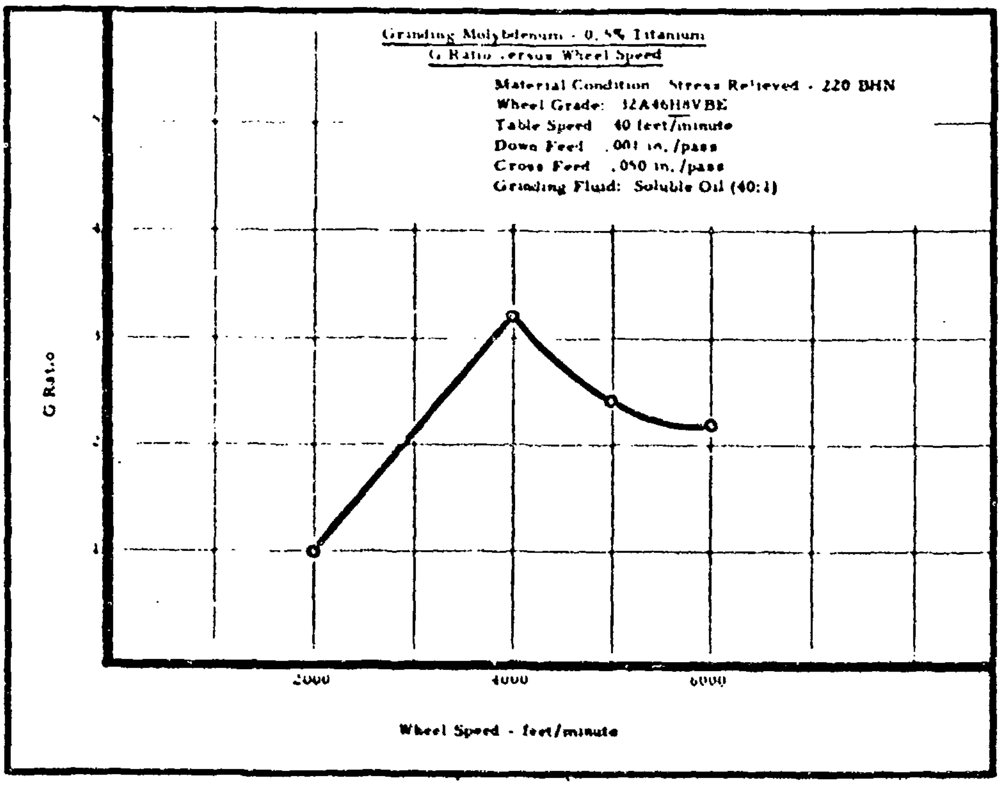
See Text, page 105

Figure 140



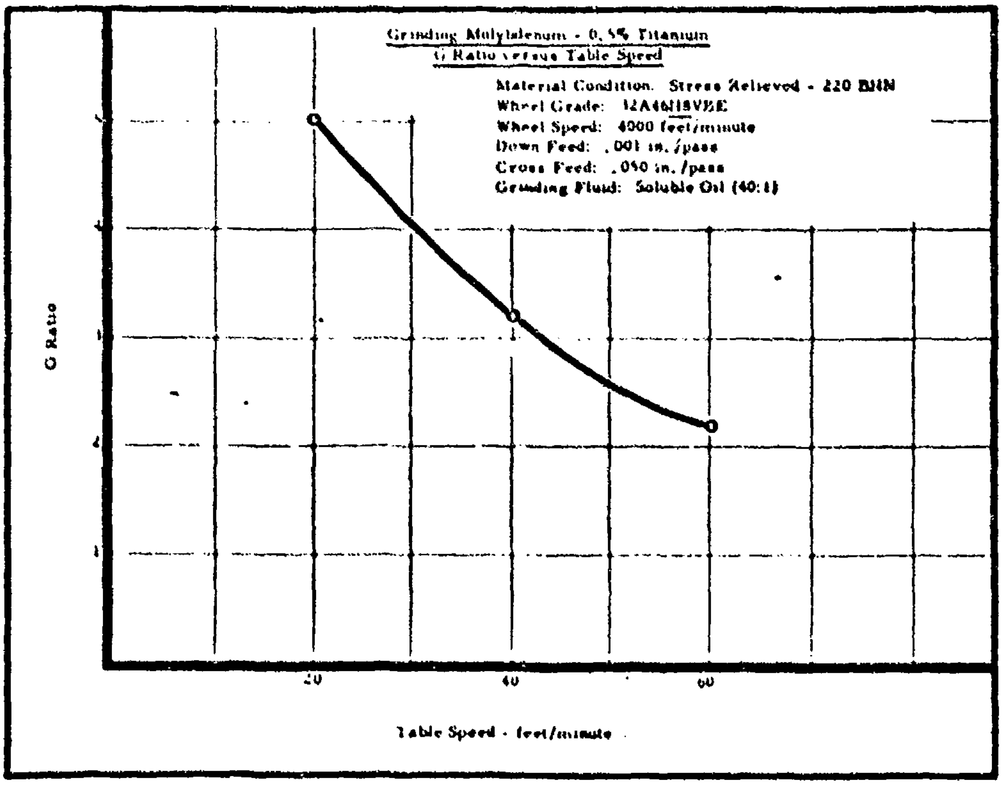
See Text, page 105

Figure 141



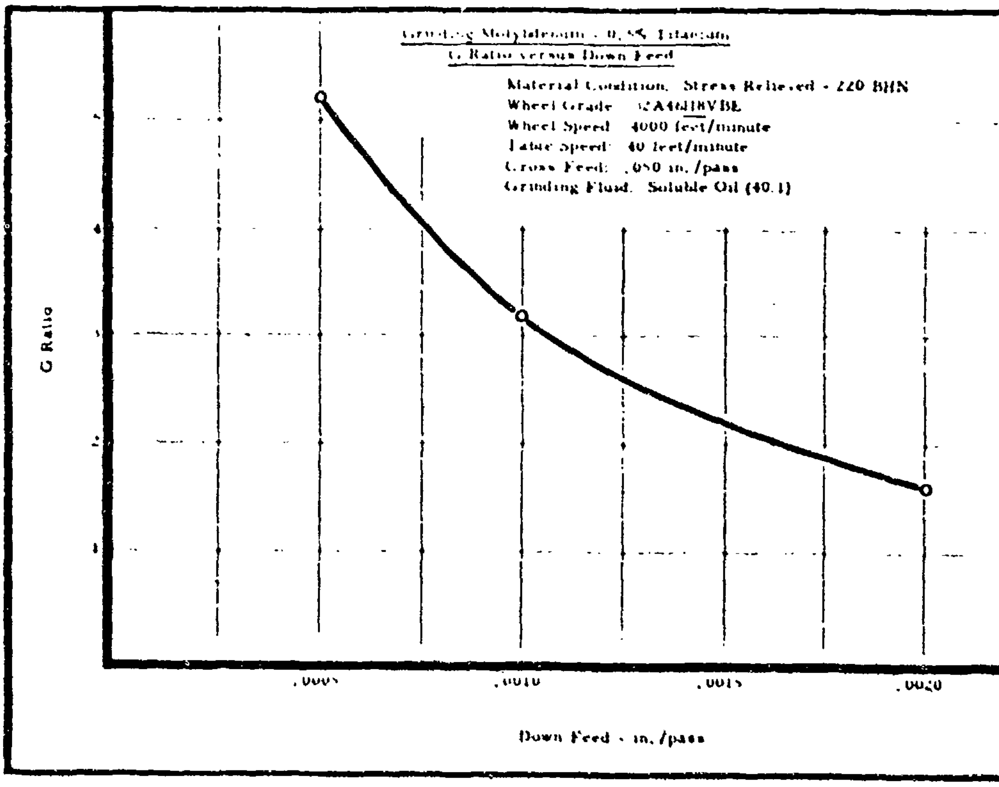
See Text, page 106

Figure 142



See Text, page 106

Figure 143



See Text, page 106

Figure 144

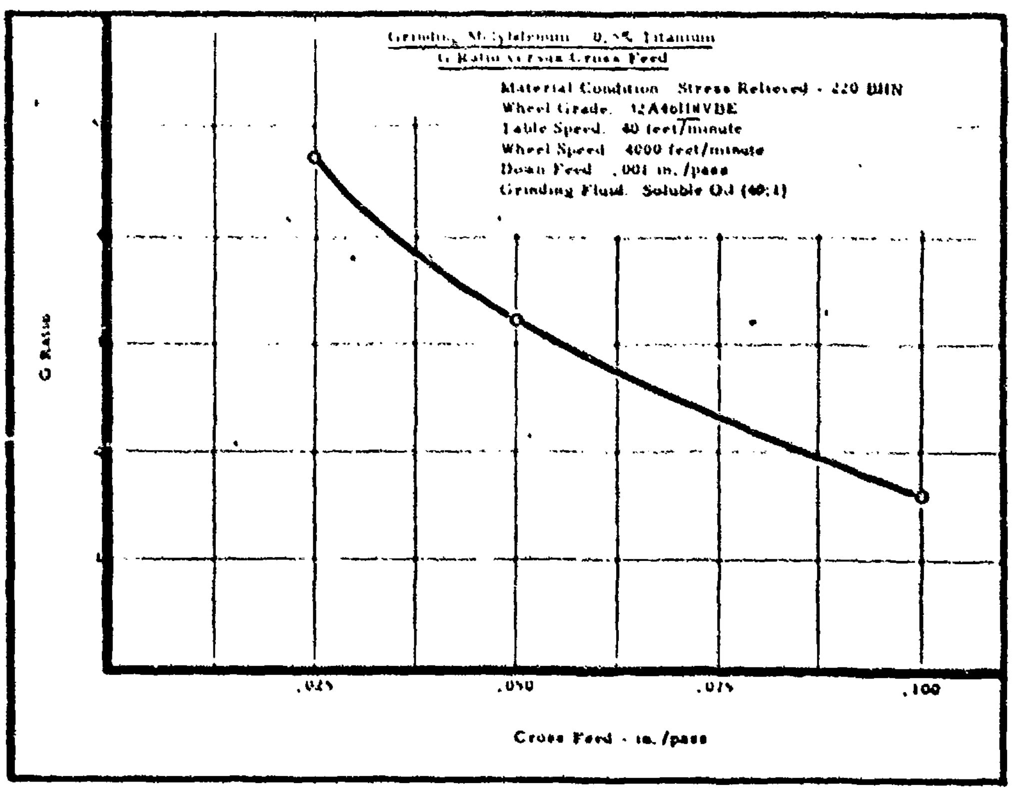


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Figure 145

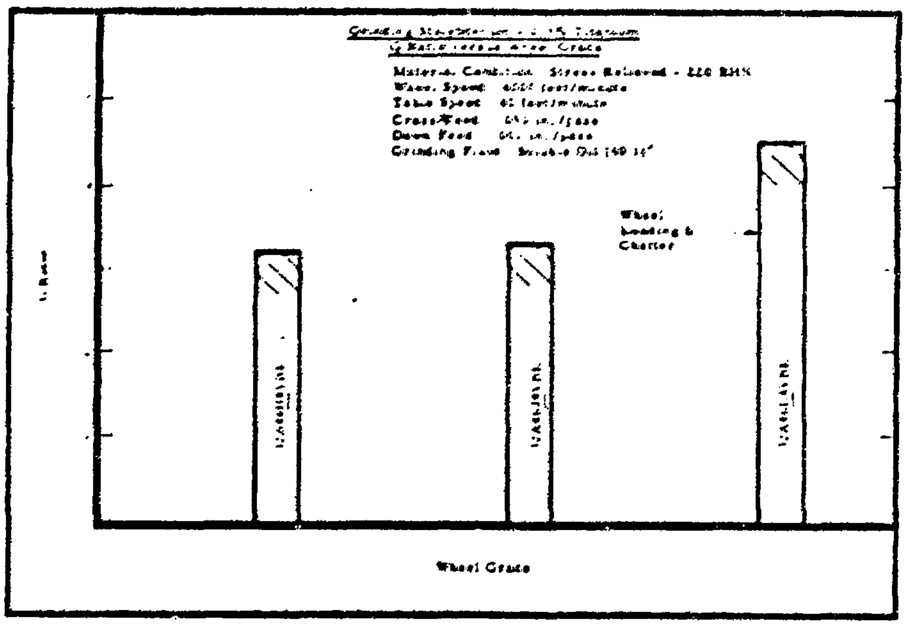

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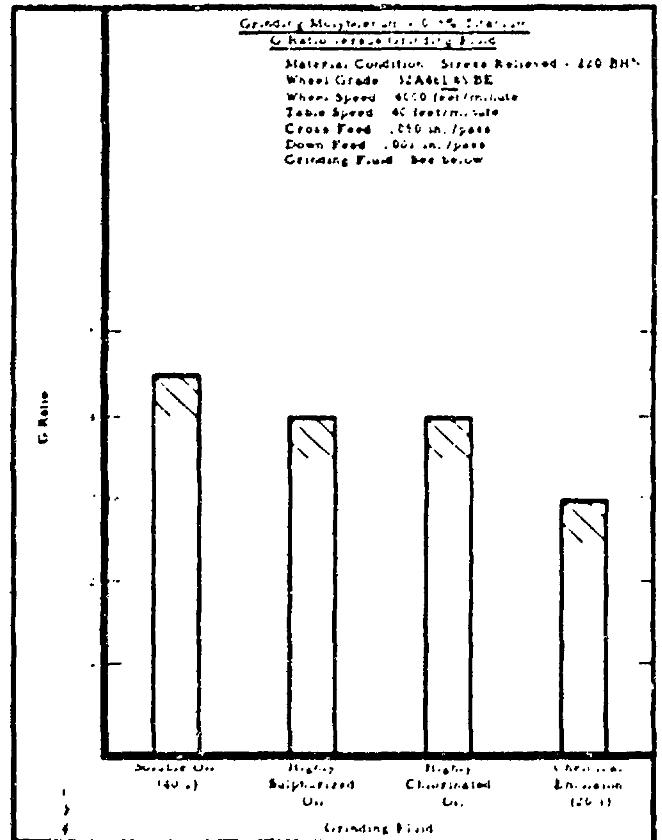
Figure 146



See Text, page 106

Figure 147

Tantalum has been of potential interest to the Aerospace Industry for many years. This interest has been based primarily on its high melting point, a characteristic which it shares with the other refractory metals. Actual use of tantalum for aerospace hardware has been limited, however, since its strength to weight ratio has not been advantageous in comparison to the other refractories.

Recent progress in alloying tantalum with tungsten has proven relatively successful, and it is in this role that tantalum appears best suited. Re-entry glide vehicles are currently being designed to operate under conditions for which this alloy is required. Rocket nozzles are presently being fabricated from this alloy. Ram-jet motors for operation above Mach 3 and some sections of turbojet engines operating above Mach 3 will also utilize the 90Ta-10W alloy.

The microstructure of 90Ta-10W is shown in Figure 148, page 126. The massive grains shown are typical of the solid solution formed by this alloy. The chemical composition is given in Table 8.

Table 8
Chemical Composition of Tantalum Alloy

	Nominal Composition, Percent		Average Hardness
	Ta	W	BHN
Tantalum alloy	89	10	241

Recommendations for Machining 90Ta-10W Alloy

The 90 tantalum - 10 tungsten alloy can be machined with high speed steel tools in the 50 to 75 feet/minute cutting speed range. With carbide tools, these speeds can be doubled. For turning and milling, tools should have plenty of rake and generous clearance angles. In drilling and tapping, copious amounts of an active cutting oil should be used.

The machining data for 90Ta-10W alloy has been reviewed, and general recommendations for machining are given in Table 9, pages 127 and 128.

Turning Tests

The curves shown in Figure 149, page 129, present the relative merits of a wide variety of tool materials in turning the 90Ta-10W alloy. Note that the cutting speeds with the carbide tool C-2 grade K-6 are 60% to 80% higher than those permitted with either the M-2 or T-15 high speed steel tools and 25% higher than with the cast alloy tools. Of the three grades of carbide tools tested, C-2, C-3 and C-6, the tool life with the C-2 grade was over 100% longer than with the C-6 and 30% longer than with the C-3 grade, see Figure 150, page 129.

Turning Tests (continued)

Comparative turning tests with three types of cutting fluids – soluble oil (1:20), highly chlorinated and highly sulphurized oils – as shown in Figure 151, page 130, indicated that soluble oil was considerably better than either of the straight oils.

The effect of feed is shown in Figure 152, page 130. The results show that the optimum feed is in the range of .006 to .010 in./rev. Tool life decreased rapidly at feeds greater than .010 in./rev. With light feeds, under .006 inches per revolution, not only was the tool life in terms of cubic inches of metal removed low, but the production rate was also low.

Face Milling Tests

Various tool materials were used in face milling the 90Ta-10W alloy. High speed steel appeared to be more practical for milling this alloy than carbide, see Figures 153 and 154, page 131. Tool life was very short with the carbide tools because of the rapid nose breakdown at the cutting speeds used. A tool life of 40 inches of work travel was obtained with a single tooth Braecut high speed steel cutter at a feed of .006 in./tooth and a cutting speed of 80 feet/minute. By increasing the feed to .010 in./tooth, the cutting speed could be increased to 100 feet/minute and still obtain the same tool life, see Figure 154, page 131. Neither the T-1 HSS nor the Stellite 98 M-2 cast alloy tool performed satisfactorily as a cutter in face milling the 90Ta-10W alloy.

The feed is critical in face milling this tantalum alloy, see Figure 155, page 132. Maximum tool life was obtained at a feed of .010 in./tooth using a Braecut HSS cutter. Cutter life is reduced almost 50% if the feed is increased to .014 inches per tooth or decreased to .006 in./tooth.

Also, unless the proper tool geometry is used, tool life is very short, see Figure 156, page 132. For example, a milling cutter with a radial rake angle of either 10° negative or 0° provided a tool life of less than five inches of work travel per tooth, while under the same milling conditions a cutter with a radial rake of 20° provided a tool life of 56 inches of work travel per tooth. The cutter life was very short over a wide range of tool geometries with carbide cutters.

Figure 157, page 133, shows that in face milling the 90Ta-10W alloy with Braecut HSS cutters the use of a soluble oil (1:20) cutting fluid resulted in a 35% improvement in tool life, over either the highly chlorinated or sulphurized oils.

End Mill Slotting Tests

As shown in Figure 158, page 133, end mill slotting can be performed at 25% higher cutting speeds with T-15 HSS cutters than with M-3 HSS cutters. The feed is very critical in this operation, see Figure 159, page 134. Doubling the feed from .002 to .004 in./tooth resulted in decreasing the tool life from 48 to 28

End Mill Slotting Tests (continued)

inches of work travel. Another important factor in end milling the 90Ta-10W alloy is the cutting fluid, as shown in Figure 160, page 134. Cutter life was twice as great with a 1:20 soluble oil as it was with either a highly sulphurized or chlorinated oil.

Drilling Tests

Data for drilling 1/16" diameter holes in tantalum alloy sheet is shown in Figure 161, page 135. Note that for the 1/16" thick sheet, a feed of .002 inches per revolution was used, while in the thicker 1/8" sheet the feed must be reduced to .001 in./rev. It should also be pointed out that when using a feed of .002 in./rev., the cutting speed used is critical; a 10% increase in speed will result in a 50% reduction in drill life.

Both the cutting speed and feed rate are also critical with larger diameter (.193") drills. The drill life curves shown in Figure 162, page 135, show that a 25% increase in cutting speed (50 to 60 feet/minute) will result in decreasing drill life from 44 holes to seven holes when a feed of .002 in./rev. is used. Also, the production rate, as shown in Figure 162, remained unchanged even when the feed was increased to .005 in./rev. since the cutting speed had to be decreased a proportional amount.

Reaming Tests

Figure 163, page 136, shows the relationship between cutting speed and reamer life. The effect of feed is also shown in this chart. Note how rapidly reamer life decreased when the cutting speed was increased beyond the optimum speed of 85 feet/minute. A 15% increase in cutting speed resulted in a 75% decrease in reamer life. At a feed of .009 in./rev. and a cutting speed of 75 feet/minute, reamer life was 64 holes. At this same cutting speed, the reamer life dropped more than 50%, to 30 holes with a feed of .005 in./rev. and to only five holes with a feed of .015 in./rev. Also, as shown in Figure 164, page 136, unless a highly chlorinated oil is used, the reamer life is apt to be very short. Less than ten holes could be reamed at the optimum speed and feed when either a soluble or a highly sulphurized oil was used.

Tapping Tests

The effect of cutting speed and cutting fluid is shown in Figure 165, page 137, for tapping the 90Ta-10W alloy. Low cutting speeds, 5 feet/minute, and a highly chlorinated oil mixed 2 to 1 with inhibited trichloroethane are required for good tap life The use of either a highly sulphurized oil or a soluble oil resulted in very poor tap life.

As shown in Figure 166, page 137, a 2 flute chip driver tap should be used when tapping this alloy. This tap style will provide about 40 holes, while not even one hole could be tapped with a 4 flute plug tap under the same conditions.

Grinding Tests

Grinding this tantalum alloy is a very difficult operation. The grinding ratios obtained ranged from less than one to five. The grinding wheel becomes loaded very rapidly which leads to a severe chatter condition. Wheels must be dressed often and flooded with the grinding fluid.

The effect of wheel speed on G ratio in grinding is presented in Figure 167, page 138, for two different grinding fluids. Note the improvement in G ratio when a wheel speed of 2000 feet/minute is used with the 5% KNO_2 solution over the higher grinding speed or with a highly chlorinated oil.

Figure 168, page 138, shows that a further improvement in G ratio was obtained when a harder wheel was used; however, chatter occurred.

As shown in Figure 169, page 139, light down feeds produced the best G ratios at a wheel speed of 2000 feet/minute using a 5% solution of KNO_2. Low table speeds of the order of 20 feet/minute and a cross feed of .025 in./pass should be used in grinding this alloy. The G ratio was about 50% higher with a 5% solution of KNO_2 than with either a soluble oil or a highly chlorinated, and 25% better than a highly sulphurized oil.

The first grinding recommendation presented in the table of recommended machining and grinding conditions was selected to obtain the highest G ratio possible for form grinding operations and to obtain maximum accuracy. The second recommendation is given, even though the grinding ratio is low, for those who cannot obtain a 2000 feet/minute wheel speed or do not wish to use a nitrite grinding fluid.

90Ta-10W Alloy, Electron Beam
Melted and Forged, 241 BHN
Microstructure is single phase consisting of large, equiaxed grains.

Magnification 100X

Etchant: 25% HNO_3
75% HF

Figure 148

See Text, page 122

TABLE 9
RECOMMENDED CONDITIONS FOR MACHINING AND GRINDING
90Ta-10W TANTALUM ALLOY, 207-241 BHN

Nominal Chemical Composition, Percent

Ta	W
89	10

Operation	Tool Material	Tool Geometry	Tool Used for Tests	Depth of Cut inches	Width of Cut inches	Feed	Cutting Speed ft./min.	Tool Life	Wear-land inches	Cutting Fluid
Turning	M-2 HSS	BR: 0° SCEA: 0° SR: 20° ECEA: 5° Relief: 5° NR: 1/64"	5/8" square solid HSS	.030	-	.009 in/rev	50	44 min.	.030	Soluble Oil (1:20)
Turning	C-2 Carbide	BR: 0° SCEA: 0° SR: 20° ECEA: 5° Relief: 5° NR: 1/64"	5/8" square brazed tool bit	.030	-	.009 in/rev	75	27 min.	.010	Soluble Oil (1:20)
Face Milling	Super HSS	AR: 0° ECEA: 10° RR: 20° CA: 45° Clearance: 10°	4" diameter single tooth face mill	.030	1.125	.010 in/tooth	80	53 in/tooth	.016	Soluble Oil (1:20)
End Mill Slotting	T-15 HSS	Helix Angle: 30° RR: 10° Clearance: 15° CA: 45° x .040"	1/2" diameter 4 tooth HSS end mill	.060	.500	.002 in/tooth	70	80 inches	.012	Soluble Oil (1:20)
End Mill Peripheral Cut	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 6° CA: 45° x .040"	1/2" diameter 4 tooth HSS end mill	.060	.560	.002 in/tooth	65	70 inches	.012	Soluble Oil (1:20)
Drilling	M-1 HSS	118° plain point 7° clearance angle	.125" diameter drill 2-3/4" long	1/8" thru hole	-	.002 in/rev	50	125 holes	.015	Highly Chlorinated Oil

TABLE 9 (continued)
RECOMMENDED CONDITIONS FOR MACHINING AND GRINDING
90Ta-10W TANTALUM ALLOY, 207-241 BHN

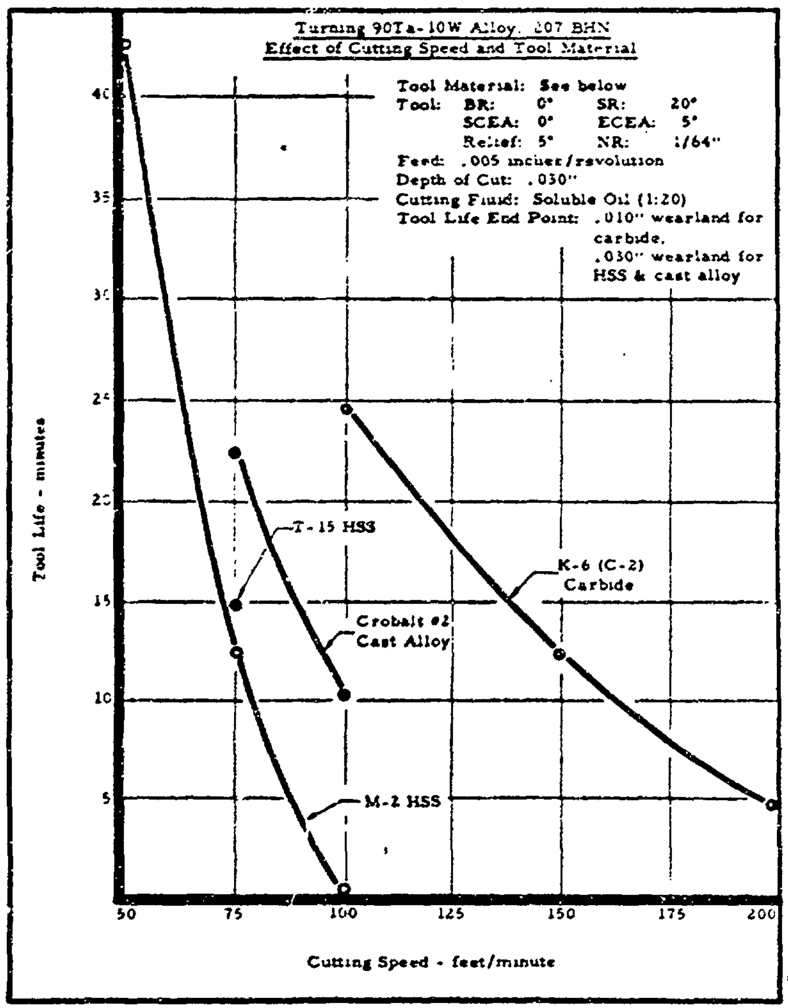
Operation	Tool Material	Tool Geometry	Tool Used for Tests	Depth of Cut inches	Width of Cut inches	Feed	Cutting Speed ft./min.	Tool Life	Wear-land inches	Cutting Fluid
Reaming	M-2 HSS	10° RH Helix CA: 45° Clearance: 10°	.213" diameter 6 flute straight shank chucking reamer	1/2" thru hole	.010" depth on hole radius	.009 in/rev	85	66	.012	Highly Chlorinated Oil
Tapping	M-10 HSS	2 flute chip driver tap 80% thread	1/4-28 NF tap	1/2" thru hole	-	-	4.5	60+ holes	-	Highly Chlorinated Oil + Inhibited Trichloroethane (2:1)

SURFACE GRINDING

Wheel Grade	Grinding Fluid	Wheel Speed feet/minute	Table Speed feet/minute	Down Feed inches/pass	Cross Feed inches/pass	G Ratio
32A46J8VBE	5%, KNO_2 Solution	2000*	20	.001	.025	4.5
32A46J8VBE	Highly Chlorinated Oil	4000	40	.002	.050	1

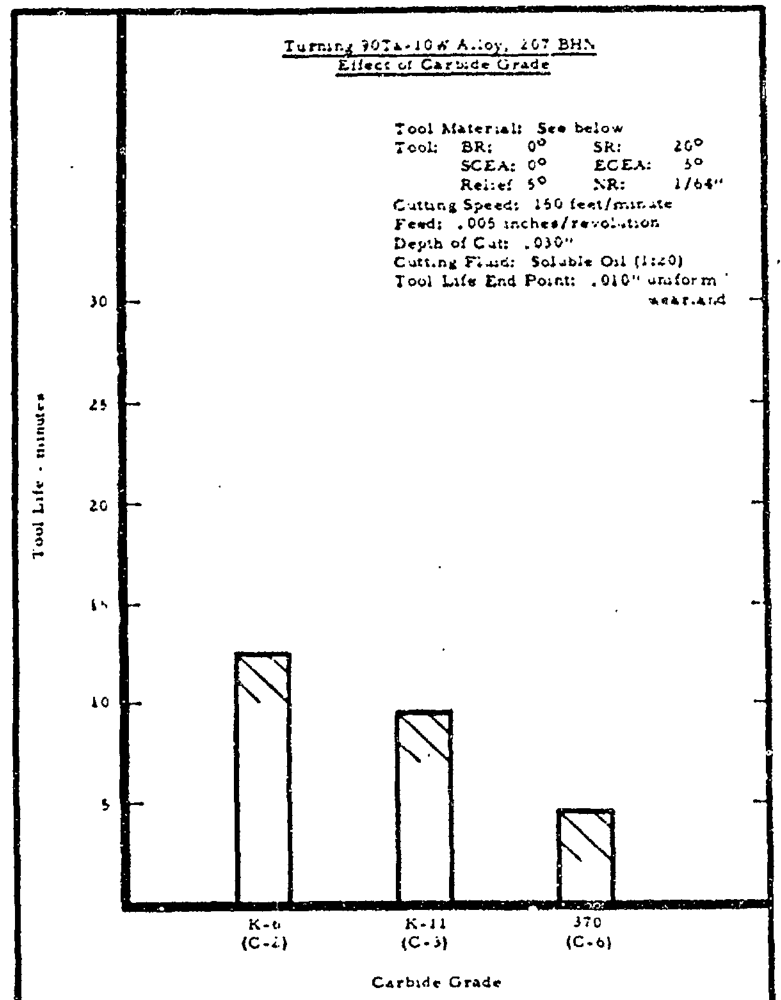
* If wheel speed of 2000 feet/minute is not available, use conditions for wheel speed of 4000 feet/minute.

See Text, page 122



See Text, page 122

Figure 149



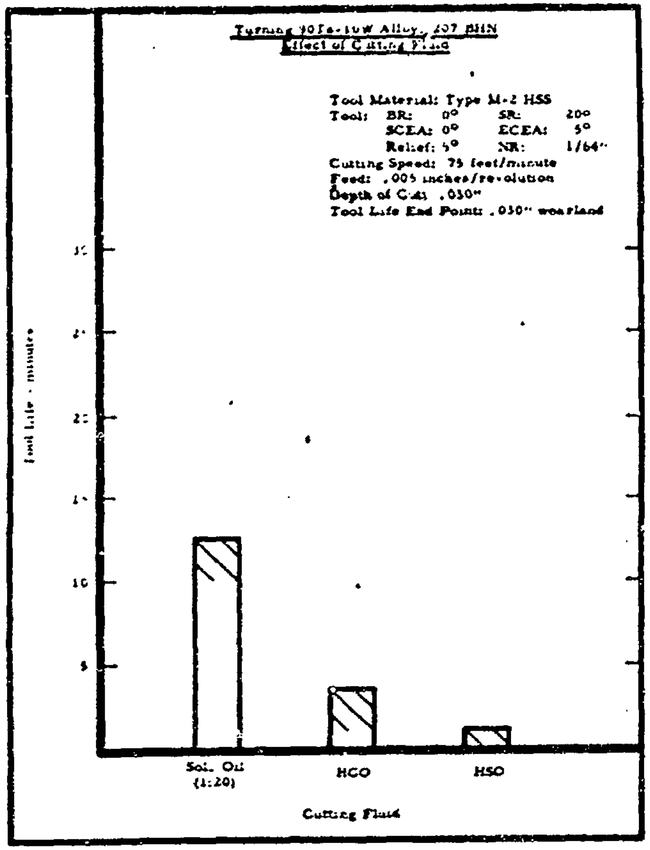


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Figure 151

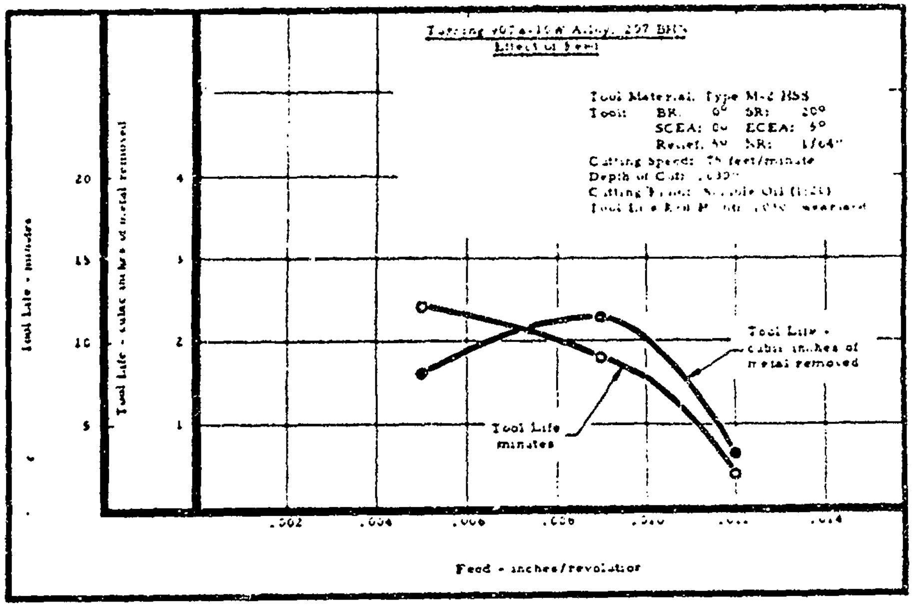

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Figure 152

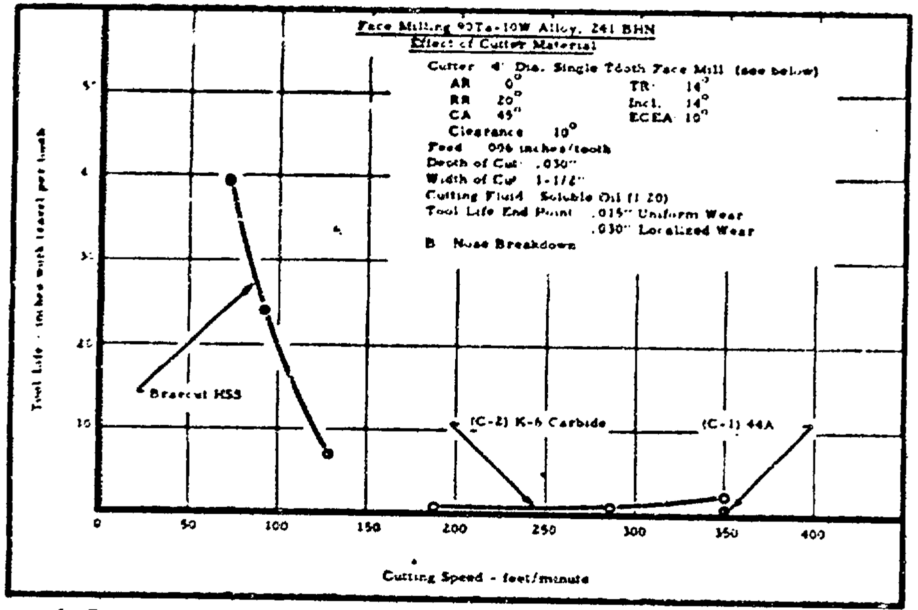

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Figure 153

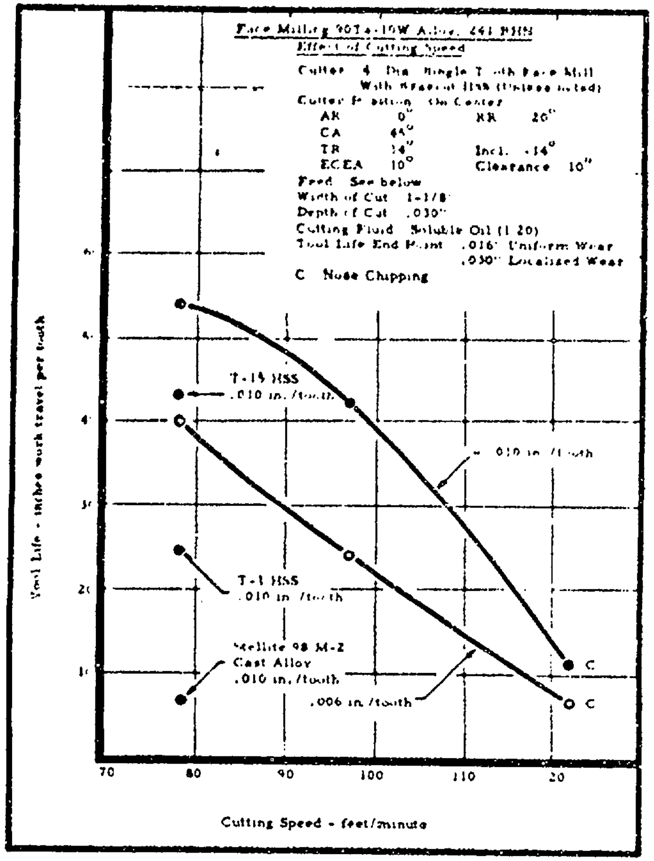

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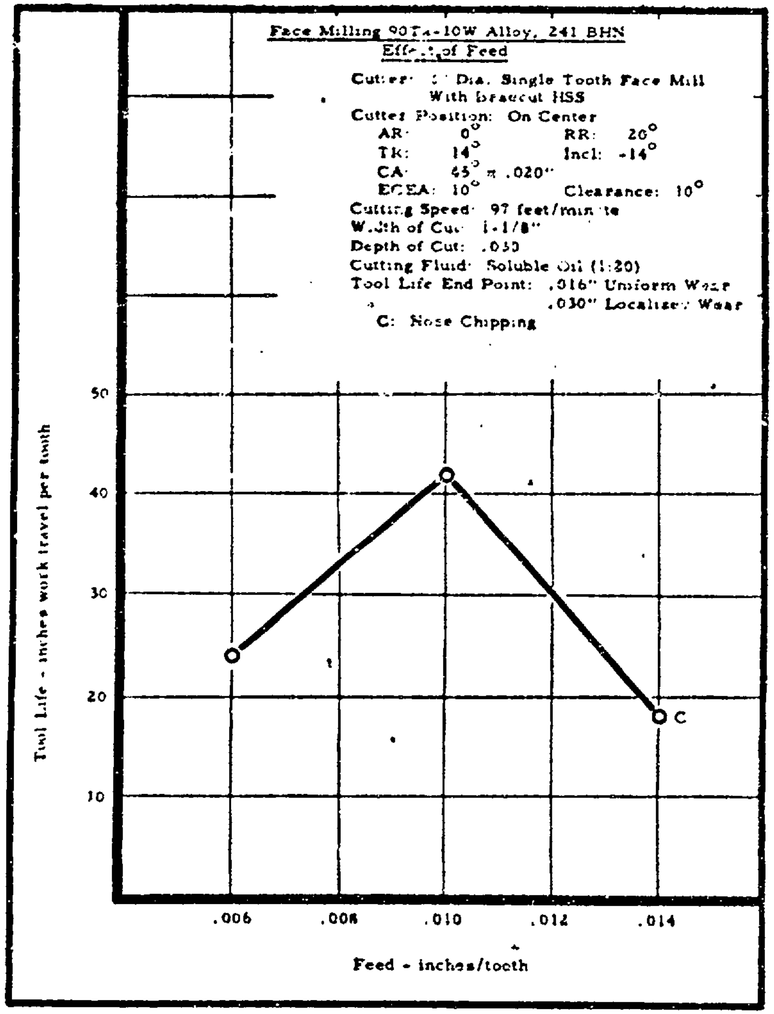
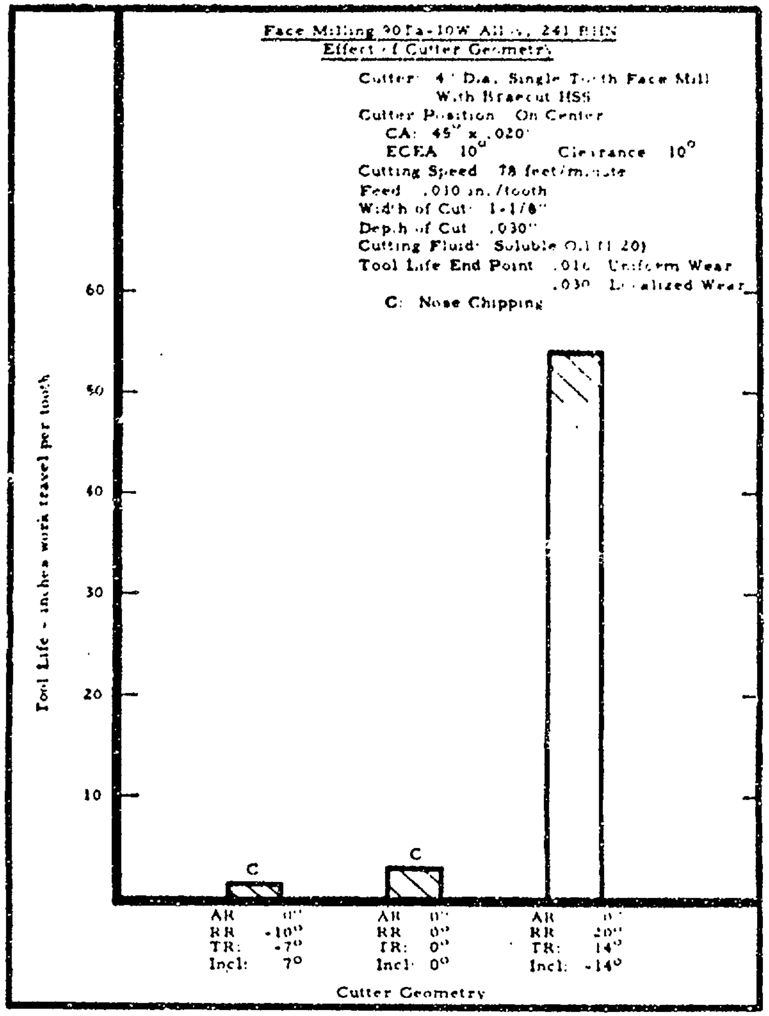
Figure 154


Face Milling 90Ta-10W Alloy, 241 BHN
Effect of Feed
Cutter: Dia. Single Tooth Face Mill With Bracut HSS
Cutter Position: On Center
AR: 0° RR: 20°
TR: 14° Incl: -14°
CA: 45° x .020"
ECEA: 10° Clearance: 10°
Cutting Speed: 97 feet/minute
Width of Cut: 1-1/8"
Depth of Cut: .030
Cutting Fluid: Soluble Oil (1:20)
Tool Life End Point: .016" Uniform Wear
.030" Localized Wear
C: Nose Chipping
Tool Life - inches work travel per tooth
Feed - inches/tooth
.006
.008
.010
.012
.014
10
20
30
40
50
C


Face Milling 90Ta-10W Alloy, 241 BHN
Effect of Cutter Geometry
Cutter: 4" Dia. Single Tooth Face Mill With Bracut HSS
Cutter Position: On Center
CA: 45° x .020"
ECEA: 10° Clearance: 10°
Cutting Speed: 78 feet/minute
Feed: .010 in./tooth
Width of Cut: 1-1/8"
Depth of Cut: .030"
Cutting Fluid: Soluble Oil (1:20)
Tool Life End Point: .016 Uniform Wear
.030 Localized Wear
C: Nose Chipping
Tool Life - inches work travel per tooth
10
20
30
40
50
60
C
C
AR 0° RR -10° TR: -7° Incl: 7°
AR 0° RR 0° TR: 0° Incl: 0°
AR 0° RR 20° TR: 14° Incl: -14°
Cutter Geometry

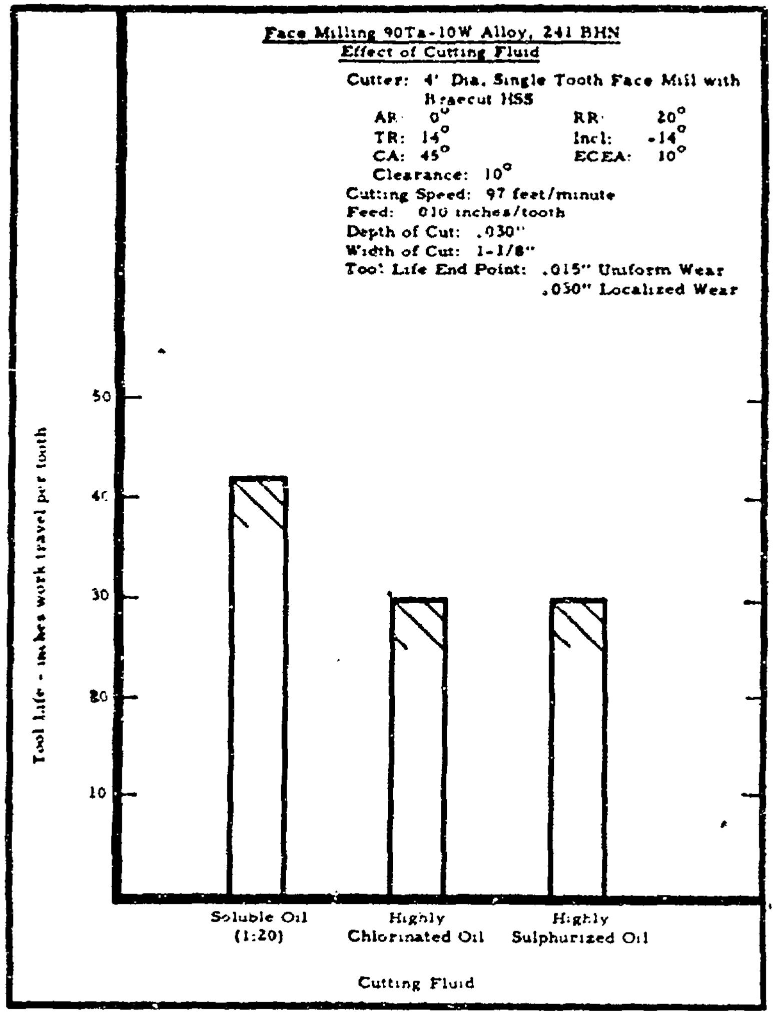


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Figure 157

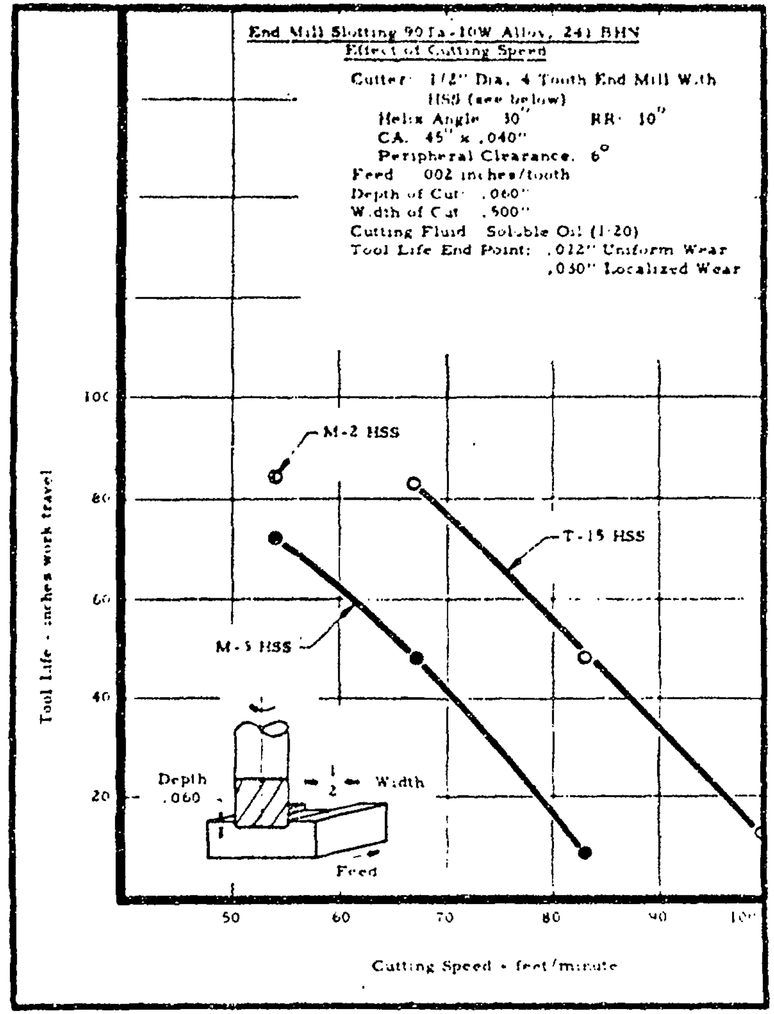

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Figure 158

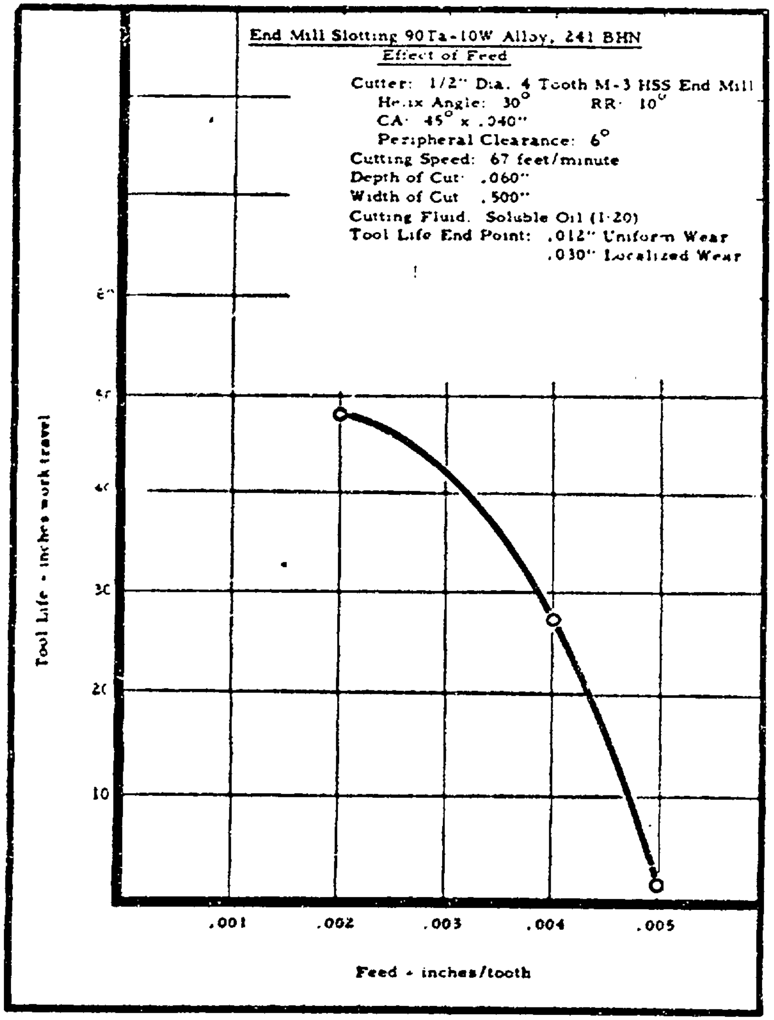

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Figure 159

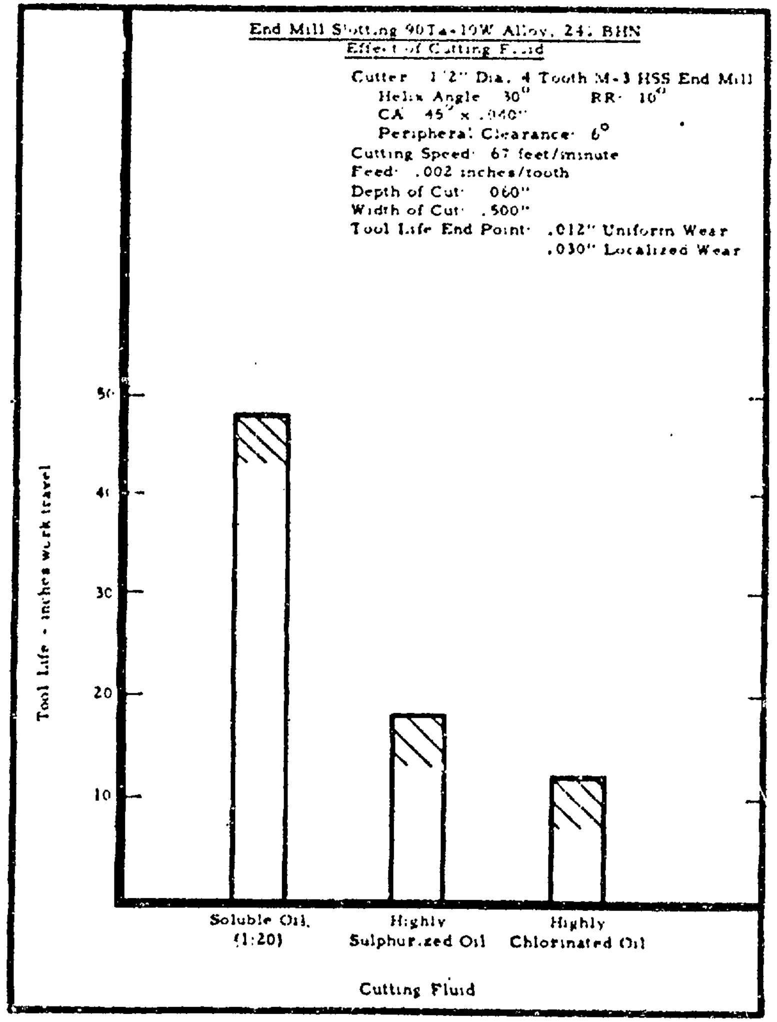

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Figure 160

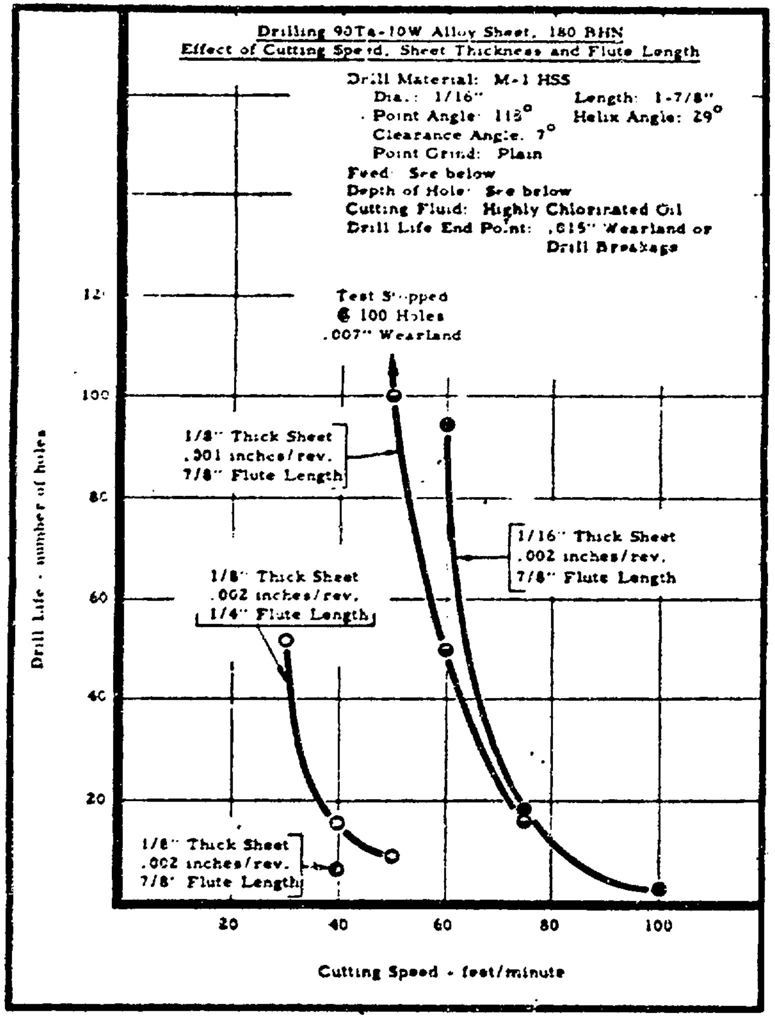

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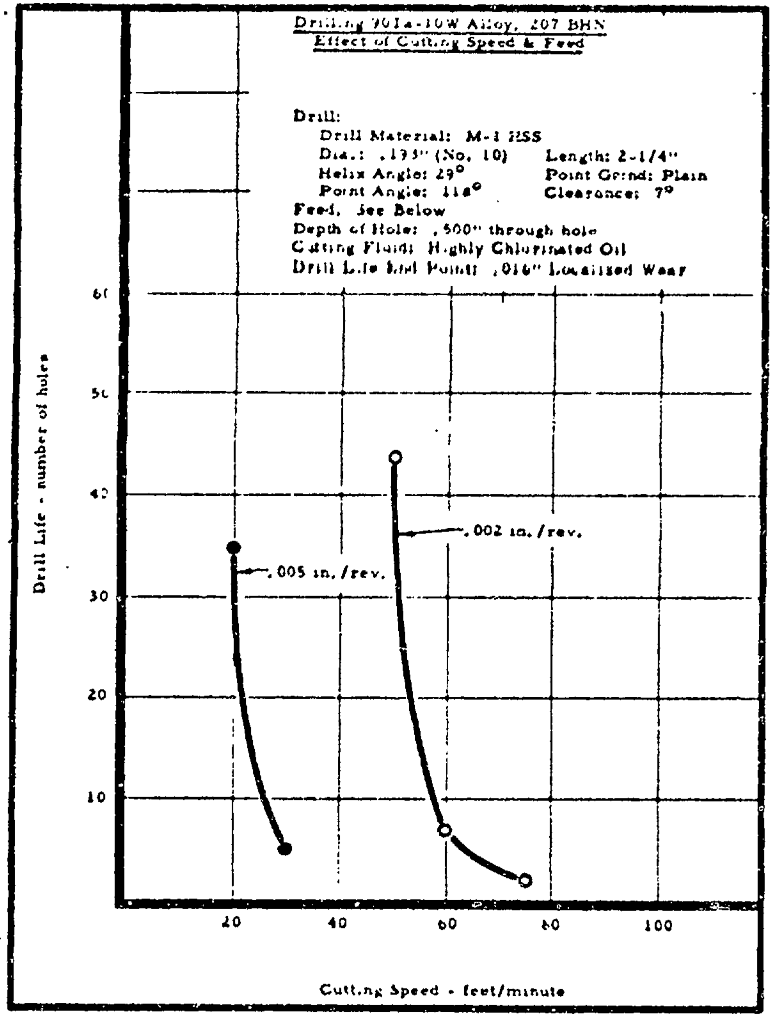
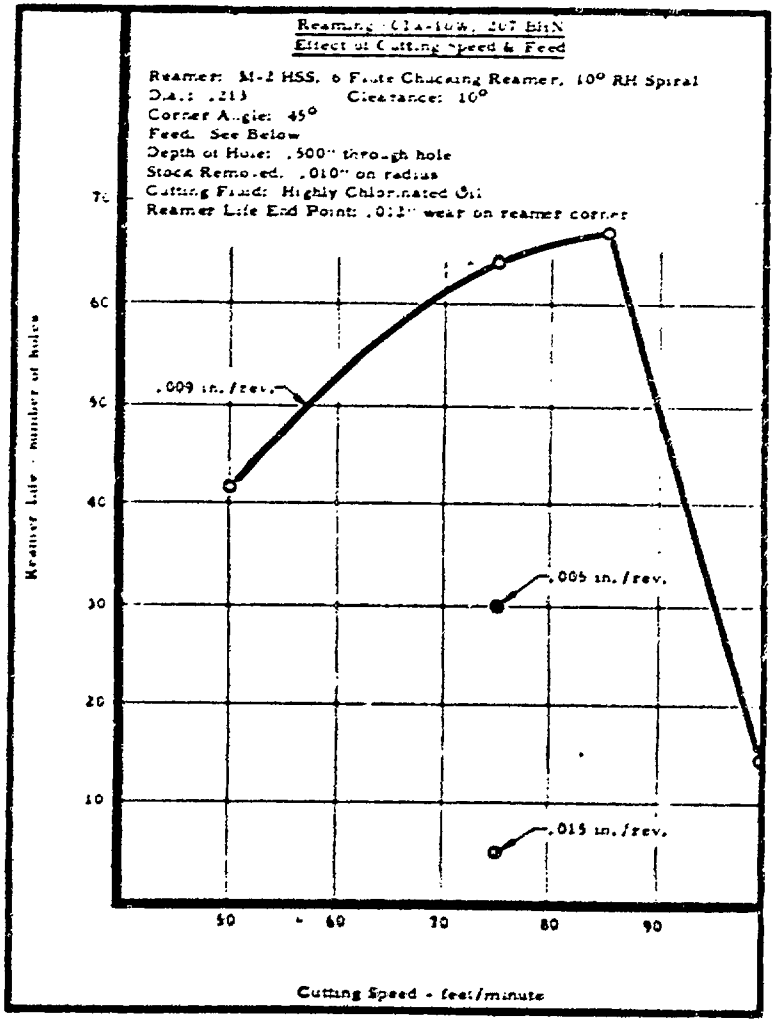
Figure 161



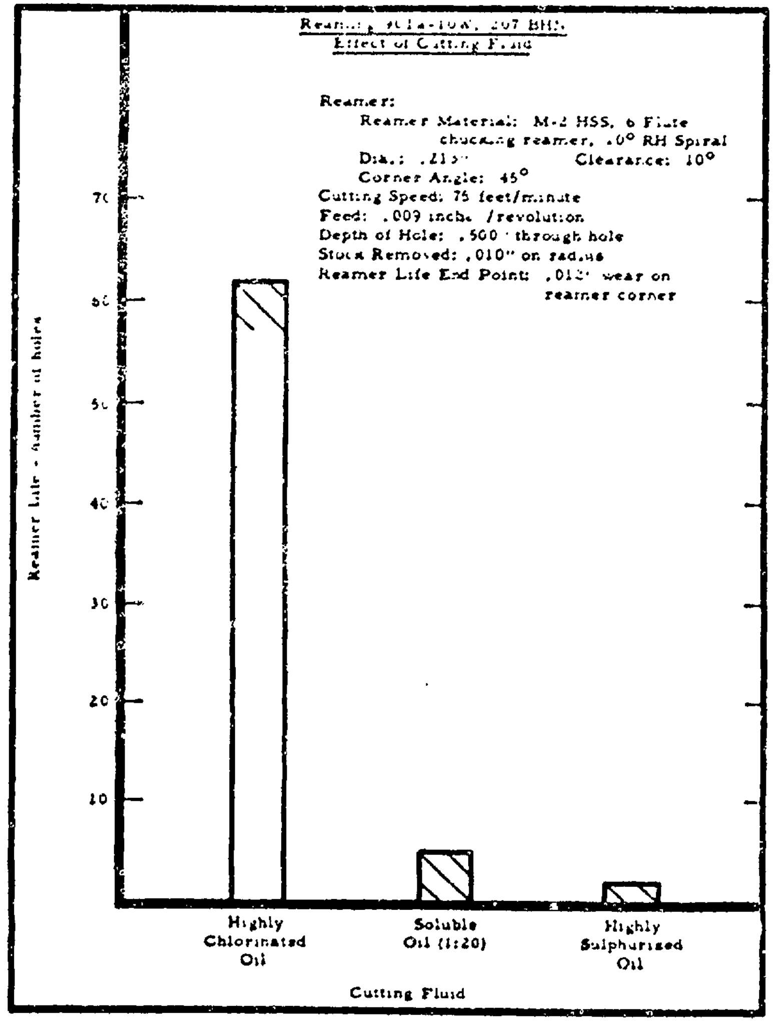
See text, page 124

Figure 162



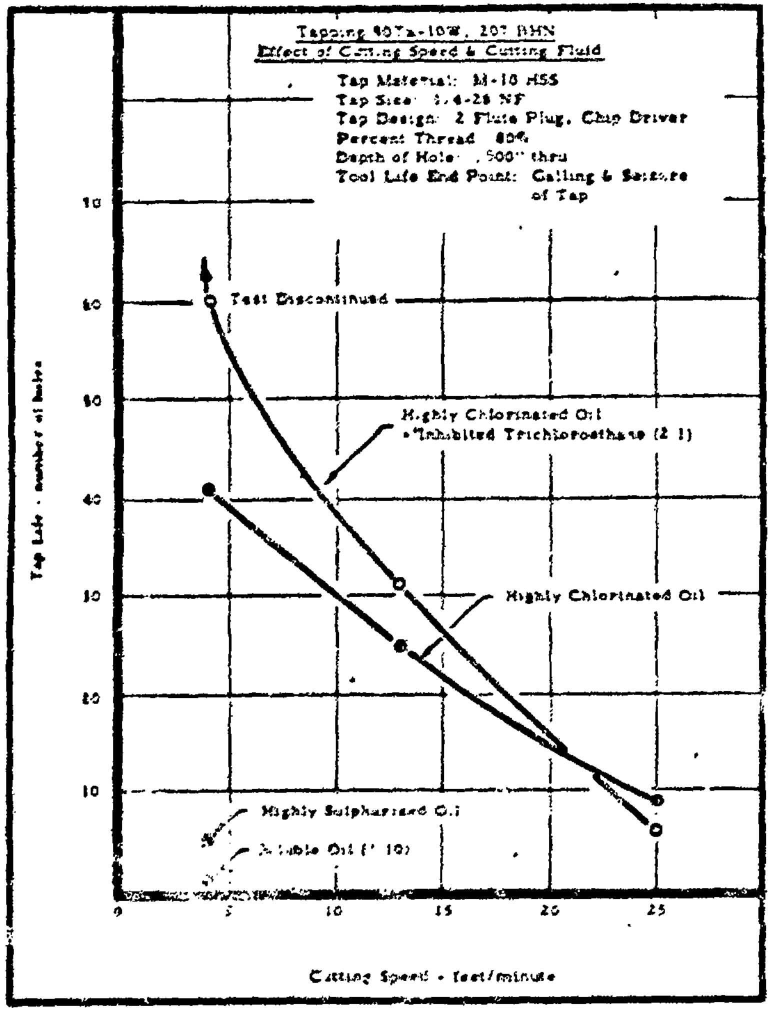
See text, page 124

Figure 163



See text, page 124

Figure 164



See Text page 124

Figure 165

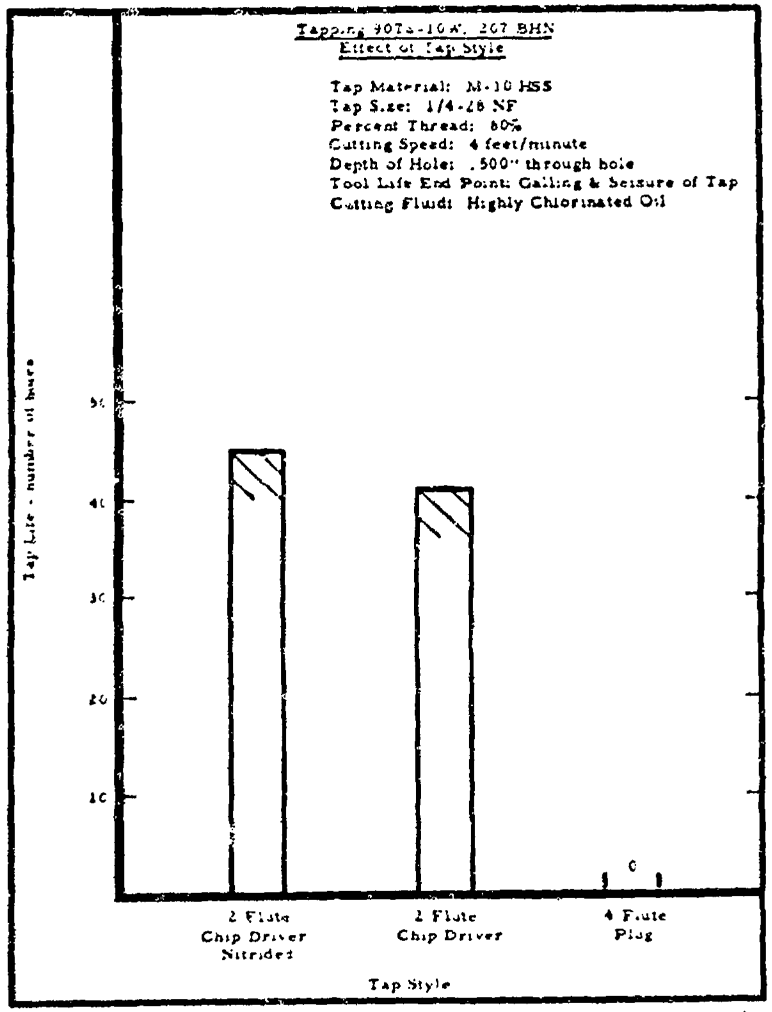


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Figure 166

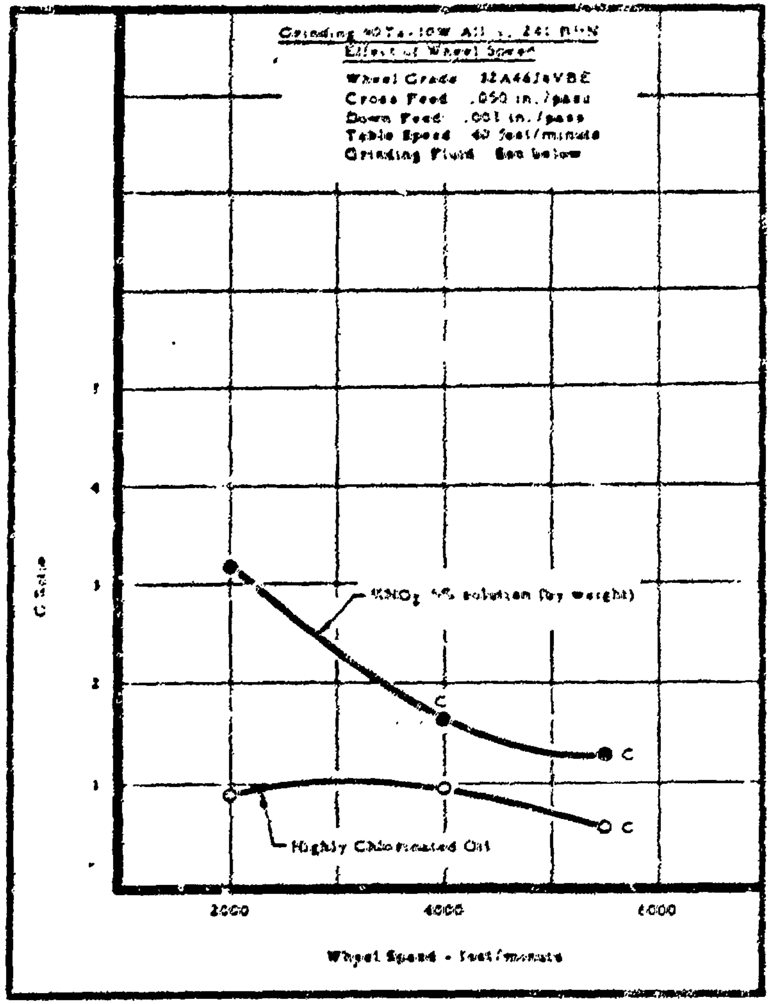

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Figure 167

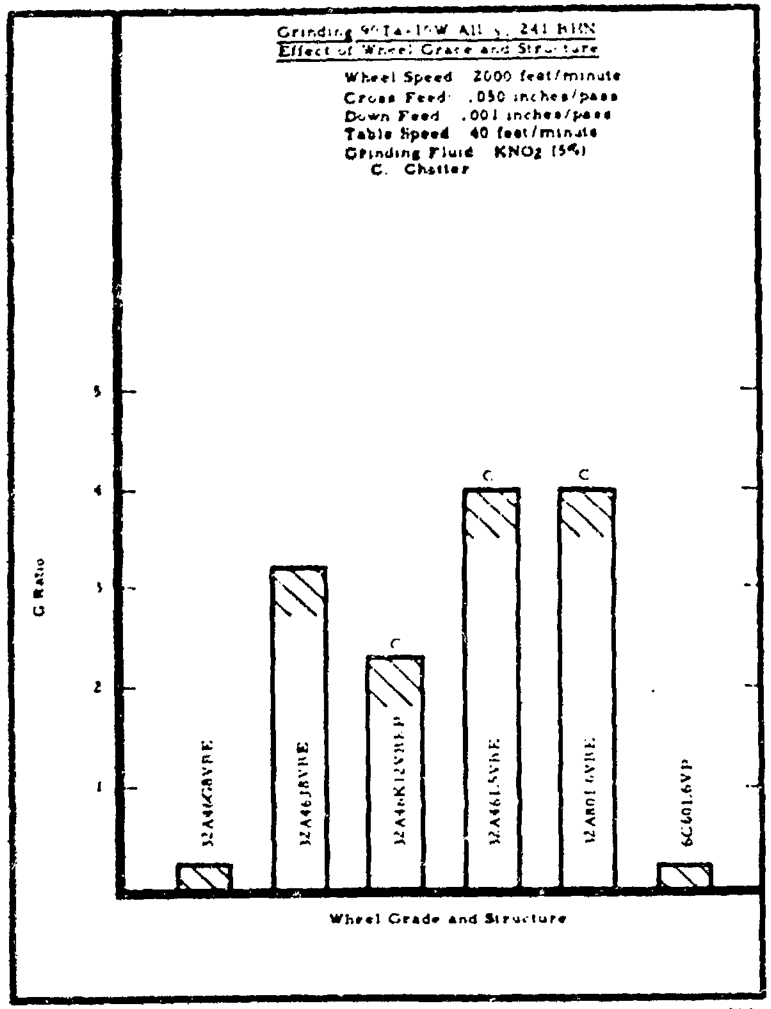

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Figure 168

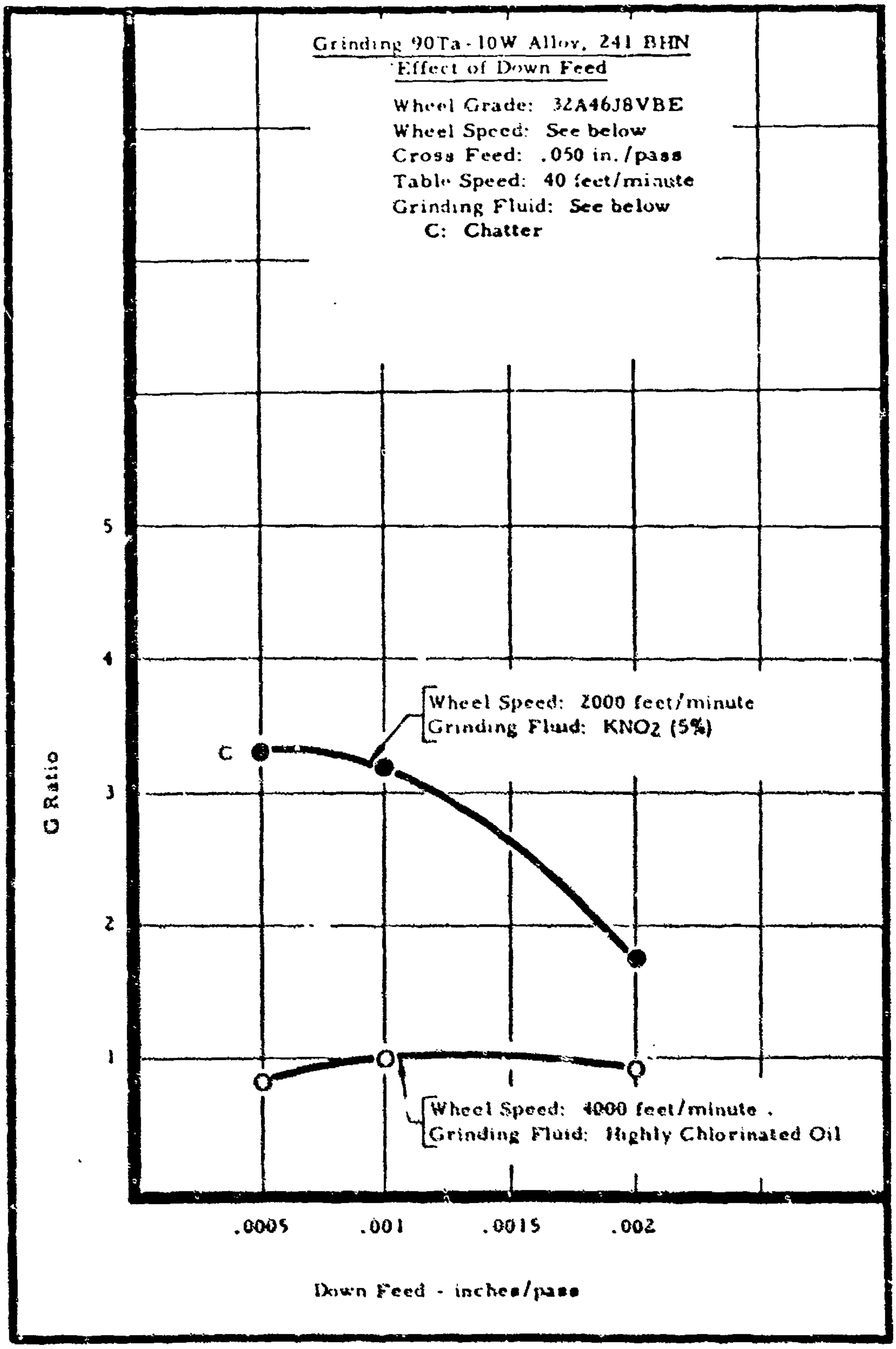

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Figure 169

B-120VCA titanium is a metastable beta titanium alloy, produced initially for missile applications where high strengths are required for short periods of time. It has been specified under a variety of designations, including VCA-beta, Ti-BV-11Cr-3Al and all-beta.

Data have confirmed that the alloy possesses excellent long-time stability at temperatures up to 600°F and can be used for short periods at temperatures above 1000°F. Combining the strength, weight and corrosion resistance advantages of titanium, these properties make the B-120VCA alloy particularly attractive for structural application in advanced aerospace weapons systems.

Heat treatment procedures for B-120VCA titanium are designed to provide a material in a highly formable condition which can be subsequently aged to provide a combination of high strength and good ductility. The solution treated material described in this report had received the following heat treatment: 1425 ± 25°F for 30 minutes, cooled in air. The aged material was given the following additional treatment: 900 ± 25°F for 60 hours, cooled in air. Microstructures illustrating both of these conditions are shown in Figure 170, page 147. The chemical composition is given in Table 10.

Table 10
Chemical Composition of B-120VCA Titanium

	Nominal Composition, Percent							Avg. Hardness
	V	Cr	Al	C	Fe	N	Ti	BHN
B-120VCA titanium	13.5	11.0	3.5	.035	.22	.02	Bal	285 (Solution Treated) 400 (Aged)

Recommendations for Machining B-120VCA Titanium

In turning, B-120VCA titanium cuts easily (low forces and good finish) provided the tools are kept sharp. In milling with carbide, prevention of cutter chipping is the chief problem. The chips remain welded on the cutting edge as each tooth emerges from the cut. Chip clogging and point smearing are the major problems encountered in drilling and tapping. A chemically active cutting fluid is required for these operations.

The data for machining B-120VCA titanium in the solution treated and in the solution treated and aged conditions has been reviewed and the general recommendations are given in Tables 11 and 12, pages 148 through 151.

Turning Tests

Tool life curves with several different high hardness high speed tools are presented in Figure 171, page 152, for turning B-120VCA titanium in the solution treated and aged condition (400 BHN). There was no appreciable difference in tool life in the four grades used.

The effect of tool geometry using carbide tools in turning B-120VCA titanium solution treated to 285 BHN is shown in Figure 172, page 152. Negative side rake and back rake angles provided the best tool life. Thus, conventional throwaway type tools have the best tool geometry for turning this material. It is also apparent from Figure 172 that a side cutting edge angle of 45° is appreciably better than a 15° lead angle.

A comparison of the tool life curves in turning B-120VCA titanium in two heat treated conditions over a range of cutting speeds is presented in Figure 173, page 153. Note that the B-120VCA titanium solution treated and aged to 400 BHN machined at speeds 30% lower than the solution treated condition at 285 BHN. The recommended cutting speed for the solution treated and aged condition is 80 feet/minute, while it is 125 feet/minute for the solution treated condition.

The use of a highly chlorinated oil permits a 10 to 15% increase in cutting speed over the soluble oil on both heat treated conditions of B-120VCA titanium.

The effect of feed on tool life in turning is shown in Figures 174 and 175, pages 153 and 154. It should be noted in comparing the two sets of tool life curves that the cutting speed for the solution treated and aged material (400 BHN) was 100 feet/minute, and 150 feet/minute for the alloy which was only solution treated (285 BHN). The tool life curves showing cubic inches of metal removed versus feed, (Figure 175), indicate that the economic feeds to use should be .009 in./rev. for the solution treated alloy (285 BHN) and .005 in./rev. for the solution treated and aged alloy (400 BHN).

Face Milling Tests

Climb cutting was employed in all of the face milling tests on the B-120VCA titanium alloy. A comparison of the super high speed steels, cast alloy and high speed steel tools is presented in Figure 176, page 154. Both the Braecut and Hypercut tools were superior to the others. The Types M-2 and T-1 high speed steels provided very short tool life. A similar comparison of the various grades of tools in face milling the same alloy in the solution treated and aged to 400 BHN is shown in Figure 177, page 155.

The effects of feed and cutting speed on tool life in face milling the B-120VCA alloy solution treated and aged to 400 BHN are shown in Figure 178, page 155. Type T-15 high speed steel tools were used in these tests. A very low cutting

speed, 25 feet/minute, is required in face milling B-120VCA titanium at 400 BHN in order to get a reasonable tool life. A feed of about .007 in./tooth appears to be the optimum feed.

The relationships of cutting speed and tool life using Braecut and Hypercut HSS tools in face milling this alloy at the two hardness levels are shown in Figures 179 and 180, page 156. A reasonable cutting speed for the solution treated condition was found to be 30 to 40 feet/minute and 25 feet/minute for the solution treated and aged condition. The tool life, per tooth, was very nearly the same for the single tooth cutter and the four tooth cutter.

The carbide grade 883 (C-2) was far superior to the C-1, C-6 and C-7 grades in face milling the solution treated B-120VCA titanium alloy at 285 BHN, as illustrated in Figure 181, page 157.

A tool life curve is shown in Figure 182, page 157, for the solution treated condition with carbide tools. It is interesting to note that the cutting speed is over 300% faster with carbide than with the super high speed steel tools for a given tool life.

As shown in Figure 183, page 158, the feed was critical. Increasing the feed from .005 to .008 in./tooth resulted in decreasing the tool life from 125 to 45 inches of work travel per tooth.

The selection of grade of carbide is very critical for face milling B-120VCA alloy solution treated and aged to 365 BHN, as shown in Figure 184, page 158. A tool life of 40 inches work travel was obtained with the best carbide used (C-2 grade), as compared to 11 inches for the next best grade.

Positive rake angle cutters perform best when face milling this alloy. Of the various tool geometries tested, (see Figure 185, page 159), a tool geometry of 10° axial rake and 0° radial rake with a 7° inclination angle provided the longest cutter life. The tool life was 40 inches of work travel per tooth, compared with less than ten inches work travel per tooth for cutters with negative rake angles.

Light feeds must also be used together with a climb cutting setup in face milling the B-120VCA titanium alloy. Figure 186, page 159, shows how much longer the tool life was when a feed of .003 in./tooth was used, as compared with a feed of .005 in./tooth. Cutter life was over three times longer with the lower feed. The main problem encountered in face milling titanium alloys with carbide tools is in preventing tool chipping. Usually the chip remains welded to the cutting edge and small nicks in the cutting edge are produced when the chip is knocked off as the tooth re-enters the workpiece. The welded area between the chip and tool is minimized by using a light feed and a climb cutting setup.

Face Milling Tests (continued)

The effect of cutting speed on tool life is also presented in Figure 186 for this alloy at 365 BHN. A cutting speed of 100 feet/minute is recommended with a feed of .002 in./tooth or a cutting speed of 65 feet/minute with a feed of .005 in./tooth.

A feed and cutting speed versus tool life chart is also shown in Figure 187, page 160. The B-120VCA titanium alloy used in obtaining these tool life results was solution treated and aged to 400 BHN. The lighter feeds are also advantageous on this alloy at the higher hardness level of 400 BHN. However, the recommended cutting speed to be used with the feed of .003 in./tooth is 70 to 80 feet/minute with highly chlorinated oil. This conclusion is further substantiated by the tool life curve shown in Figure 188, page 160.

End Milling Tests

The effect of cutting speed on tool life in end mill slotting B-120VCA titanium in two different heat treated conditions is presented in Figure 189, page 161. The cutting speed for a given tool life on the solution treated alloy (285 BHN) was about 10% higher than with the aged alloy (400 BHN).

As shown in Figure 190, page 161, the feed was very critical in both heat treated conditions. Doubling the feed from .002 to .004 in./tooth resulted in decreasing the tool life from a reasonable value to a very short tool life. The type of cutting fluid selected did not affect tool life to any great extent, see Figure 191, page 162; however, heavy duty soluble oil at 1:20 dilution was slightly better than the other fluids tested.

The effect of feed on cutter life in peripheral end milling the B-120VCA titanium alloy at 400 BHN is shown in Figure 192, page 162. Type M-2 high speed steel end mills were used in these tests. Feeds in the range of .001 to .002 in./tooth appear to be required in order to obtain a reasonable tool life at a cutting speed of 51 feet/minute, which was used in this series of tests.

A comparison of cutter life at two different feeds is shown in Figure 193, page 163, when peripheral end milling the B-120VCA titanium alloy solution treated to 285 BHN. While the cutter life was longer with the lower feed of .002 inches per tooth, a feed of .004 in./tooth will provide the same cutter life if the cutting speed is reduced about 15%. The production rate is 70% higher when using a feed of .004 in./tooth for equivalent tool life.

Figure 194, page 163, shows that a feed of .002 in./tooth is preferable to a feed of .001 in./tooth over a range of cutting speeds. Not only is cutter life longer with the feed of .002 in./tooth, but the production rate is doubled.

In end milling deep pockets using the periphery of the end mill, a certain amount of cutter deflection takes place which results in a tapered surface along the axial length of the cut. This condition is illustrated by Figure 195, page 164.

End Milling Tests (continued)

The effects of end mill flute length, axial length of cut and depth of cut on cutter deflection are shown in Figure 196, page 164, when peripheral end milling B-120VCA titanium aged to 400 BHN. This chart shows that maximum cutter deflection occurred when relatively long end mills were used to take heavy depths of cut. If a long end mill must be used, the only way to minimize deflection is to reduce the depth of cut. When using a 4" flute length 3/4" diameter end mill taking a 4" axial length of cut, a deflection of .024" was observed for a .050" depth of cut. When the depth of cut was reduced to .010", cutter deflection was reduced to about .007". As one might expect reducing the flute length of the cutter will permit greater depths of cut to be taken for a given cutter deflection. Figures 197 and 198, page 165, show the cutter deflection when end milling with various lengths of cutters and with several different lengths of cut.

Drilling Tests

Light feeds must be used in drilling the B-120VCA titanium alloy aged to 400 BHN, see Figure 199, page 166. Unless a feed of .0005 to .002 in./rev. is used, drill life is very low even at very low cutting speeds of 20 feet/minute. These results were obtained with Type T-15 high speed steel drills. A comparison of the results obtained with M-1, M-3 and T-15 high speed steel drills is presented in Figure 200, page 166.

Reaming Tests

In reaming the 400 BHN B-120VCA titanium alloy, heavier feeds than are used in drilling should be used. Figure 201, page 167, shows the advantage of a feed of .005 in./rev. over a wide range of reaming speeds. At a reaming speed of 30 feet/minute, the reamer life with a feed of .005 in./rev. was 80% greater than at a feed of .002 in./rev. and 130% greater than at a feed of .001 inches per revolution.

Tapping Tests

In tapping the B-120VCA titanium alloy aged to 400 BHN, the design of the tap is very critical. Note in Figure 202, page 167, that the tap life was negligible for both the 3 and 4 flute plug taps; however, more than 100 holes were tapped with a 2 flute chip driver tap.

When using the proper tap at a cutting speed of 9 feet/minute, a reasonable number of holes can be tapped even with a 75% thread. If the speed is increased to 13 feet/minute, as shown in Figure 203, page 168, tap life will decrease to 50 holes. A highly chlorinated cutting oil must be used in tapping this alloy.

Grinding Tests

B-120VCA titanium can be ground effectively with silicon carbide wheels by decreasing the wheel speed to 4000 feet/minute. The surface finish produced ranged from 15 to 40 microinches, depending upon the grinding conditions. The better surface finish was obtained under the grinding conditions which provided a relatively high G ratio.

Surface damage produced by grinding does not appear to be an important problem in grinding B-120VCA titanium. No evidence of surface damage was observed for a variety of grinding conditions, nor was there any evidence of a phase transformation at the surface of the severely ground specimens.

Figures 204 through 209, pages 168 through 171, show the results obtained when surface grinding the B-120VCA titanium alloy solution treated and aged to 400 BHN. The effect of wheel grade is shown in Figure 204, page 168, when using silicon carbide and aluminum oxide grinding wheels. The best G ratio (9.5) was obtained using a 39C60K8VK wheel. Softer or harder silicon carbide wheel grades did not increase the grinding ratio. Grinding ratios of less than two were obtained when aluminum oxide grinding wheels were used on this alloy.

The effect of wheel speed when using several silicon carbide wheel grades is shown in Figure 205, page 169. The best G ratio (12.5) was obtained with a K grade wheel operating at 3000 feet/minute. The G ratio was lower for wheel speeds above and below 3000 feet/minute. The other wheel grades tested, H, I and J, provided a maximum G ratio of ten at a wheel speed of 4000 feet/min.

Figure 206, page 169, shows the effect of down feed when surface grinding the B-120VCA alloy aged at 400 BHN. These tests were run using a 39C60K8VK wheel operating at 3000 feet/minute. The G ratio decreased from 16 to 7 when the down feed was increased from .0005 in./pass to .002 in./pass.

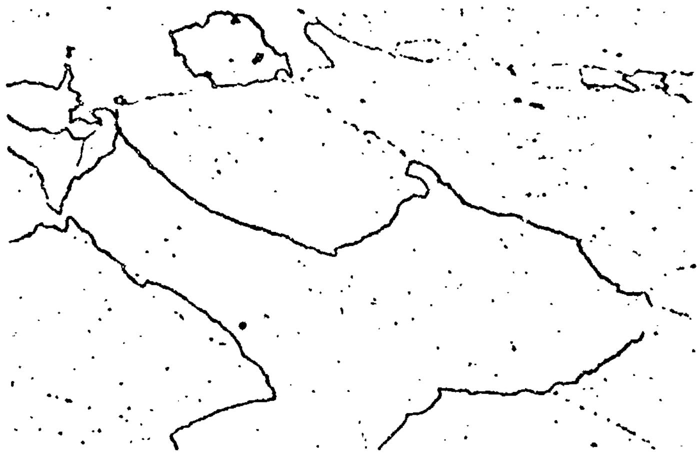
As the table speed was increased from 20 feet/minute to 40 feet/minute, the G ratio remained constant at 12.5 when grinding this alloy with a K grade silicon carbide wheel at 3000 feet/minute. See Figure 207, page 170. However, when the table speed was increased to 60 feet/minute, the G ratio was reduced to about nine.

Figure 208, page 170, shows the effect of cross feed on G ratio. The best G ratio, 12.5, was obtained when a cross feed of .050 in./pass was used. The G ratio decreased slightly when higher or lower cross feeds were used.

A highly chlorinated oil provides the best grinding ratio when grinding this alloy over a range of wheel speeds from 2000 to 6000 fee/minute. This can be seen in Figure 209, page 171. A 5% solution of potassium nitrite was next best, and the poorest grinding fluid tested was a highly sulphurized oil.

Grinding Tests (continued)

Grinding ratio of about ten can be obtained by following the recommendations given in Table 12, pages 150 and 151. This recommendation is not intended to solve specific problems, but rather to provide a starting point for a high G ratio. The relative importance of finish accuracy, rate of production, costs, equipment, etc., will govern the setup details in its final analysis.



Solution Treated Condition, 285 BHN
Microstructure consists essentially of single phase matrix.
Magnification: 100X Etchant: 1 part HF
1 part HNO_3
2 parts Glycerol

Solution Treated and Aged, 400 BHN
Microstructure shows extensive formation of precipitates.
Magnification: 100X Etchant: 1 part HF
1 part HNO_3
2 parts Glycerol

Figure 170

TABLE 11

RECOMMENDED CONDITIONS FOR MACHINING AND GRINDING B-120VCA TITANIUM SOLUTION TREATED TO 285 BHN

Nominal Chemical Composition, Percent

V	Cr	Al	C	Fe	N	Ti
13.5	11.0	3.5	.035	.22	.02	Bal.

Operation & Workpiece Hardness	Tool Material	Tool Geometry	Tool Used for Tests	Depth of Cut inches	Width of Cut inches	Feed	Cutting Speed ft/min.	Tool Life	Wear-land inches	Cutting Fluid
Turning	C-2 Carbide	BR: -5° SCEA:15° SR: -5° ECEA:15° Relief: 5° NR: 1/32	1/2 x 1/2 x 1/8" Throwaway Insert	.100	--	.009 in/rev	125	35 min.	.016	Highly Chlorinated Oil
Turning	Super HSS	BR: 0° SCEA: 45° SR: 15° ECEA: 10° Relief: 5° NR: .030"	5/8" square Tool Bit	.100	--	.009 in/rev	25	15 min.	.060	Highly Chlorinated Oil
Face Milling	C-2 Carbide	AR: 10° ECEA:10° RR: 0° CA: 45° Clearance: 10°	4" diameter Single Tooth Face Mill	.100	2	.005 in/tooth	120	125 in/tooth	.030	Highly Chlorinated Oil
Face Milling	Super HSS	AR: 10° ECEA:10° RR: 0° CA: 45° Clearance: 10°	4" diameter Single Tooth Face Mill	.060	2	.010 in/tooth	40	45 in/tooth	.040	Highly Chlorinated Oil
End Mill Slotting	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 15° CA: 45° x .040	3/4" diameter Four Tooth HSS End Mill	.125	.750	.002 in/tooth	40	150 inches	.012	Heavy Duty Soluble Oil (1:20)
Peripheral End Milling	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 15° CA: 45° x .040"	3/4" diameter Four Tooth HSS End Mill	.125	.750	.004 in/tooth	54	233 inches	.012	Highly Chlorinated Oil

TABLE 11 (continued)

RECOMMENDED CONDITIONS FOR MACHINING AND GRINDING
B-120VCA TITANIUM SOLUTION TREATED TO 285 BHN

Operation & Workpiece Hardness	Tool Material	Tool Geometry	Tool Used for Tests	Depth of Cut inches	Width of Cut inches	Feed	Cutting Speed ft./min	Tool Life	Wear-land inches	Cutting Fluid
Drilling	M-1 HSS	118° Plain point 7° Clearance	1/4" diameter Drill Screw Machine Length	1/2" thru	--	.001 in/rev	20	70 holes	.015	Highly Chlorinated Oil
Reaming	M-2 HSS	10° R.H. Helix CA: 45° Clearance: 10°	.272 diameter Six Flute Straight Shank Chucking Reamer	1/2" thru	--	.005 in/rev	30	180 holes	.015	Highly Chlorinated Oil
Tapping	M-10 HSS	Two Flute Chip Driver Tap 75% Thread	5/16-24 NF Tap	1/2" thru	--	--	9	100+ holes	Tap Breakage	Highly Chlorinated Oil

TABLE 12
RECOMMENDED CONDITIONS FOR MACHINING AND GRINDING
B-120VCA TITANIUM SOLUTION TREATED AND AGED TO 400 BHN

Nominal Chemical Composition, Percent

V	Cr	Al	C	Fe	N	Ti
13.5	11.0	3.5	.035	.22	.02	Bal.

Operation	Tool Material	Tool Geometry	Tool Used for Tests	Depth of Cut inches	Width of Cut inches	Feed	Cutting Speed ft./min.	Tool Life	Wear-land inches	Cutting Fluid
Turning	C-2 Carbide	BR: -5° SCEA: 15° SR: -5° ECEA: 15° Relief: 5° NR: 1/32	1/2 x 1/2 x 1/8" Throwaway Insert	.100	--	.009 in/rev	100	20 min.	.016	Highly Chlorinated Oil
Turning	Super HSS	BR: 0° SCEA: 45° SR: 15° ECEA: 10° Relief: 5° NR: 1/32	5/8" square Tool Bit	.100	--	.009 in/rev	25	15 min.	.060	Highly Chlorinated Oil
Face Milling	C-2 Carbide	AR: 10° ECEA: 10° RR: 0° CA: 45° Clearance: 10°	4" diameter Single Tooth Face Mill	.100	2	.003 in/tooth	78	90 in/tooth	.016	Highly Chlorinated Oil
Face Milling	Super HSS	AR: 10° ECEA:10° RR: 0° CA: 45° Clearance: 10°	4" diameter Single Tooth Face Mill	.100	2	.007 in/tooth	27	55 in/tooth	.040	Highly Chlorinated Oil
End Mill Slotting	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 15° CA: 45° x .040	3/4" diameter Four Tooth HSS End Mill	.125	.750	.002 in/tooth	40	140 inches	.012	Heavy Duty Soluble Oil (1:20)
Peripheral End Milling	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 15° CA: 45° x .040	3/4" diameter Four Tooth HSS End Mill	.125	.750	.002 in/tooth	50	120 inches	.012	Highly Chlorinated Oil

TABLE 12 (continued)

RECOMMENDED CONDITIONS FOR MACHINING AND GRINDING
B-120VCA TITANIUM SOLUTION TREATED AND AGED TO 400 BHN

Operation	Tool Material	Tool Geometry	Tool Used for Tests	Depth of Cut inches	Width of Cut inches	Feed	Cutting Speed ft./min	Tool Life	Wear-land inches	Cutting Fluid
Drilling	M-1 HSS	118° Plain point 7° Clearance	1/4" diameter Drill Screw Machine Length	1/2" thru hole	--	.001 in/rev	20	75 holes	.015	Highly Chlorinated Oil
Reaming	M-2 HSS	10° R.H. Helix C.A: 45° Clearance: 10°	.272 diameter Six Flute Straight Shank Chucking Reamer	1/2" thru hole	.010" depth on hole radius	005	30	170 holes	.015	Highly Chlorinated Oil
Tapping	M-10 HSS	Two Flute Chip Driver Tap 75% Thread	5/16-24"NF Tap	1/2" thru hole	--	--	9	100+ holes	Tap Breakage	Highly Chlorinated Oil

Surface Grinding

Wheel Grade	Grinding Fluid	Wheel Speed ft./min.	Table Speed ft./min.	Down Feed in./pass	Cross Feed in./pass	G-Ratio
39C60K8VK	Highly Chlorinated Oil	3000	40	.001	.050	13

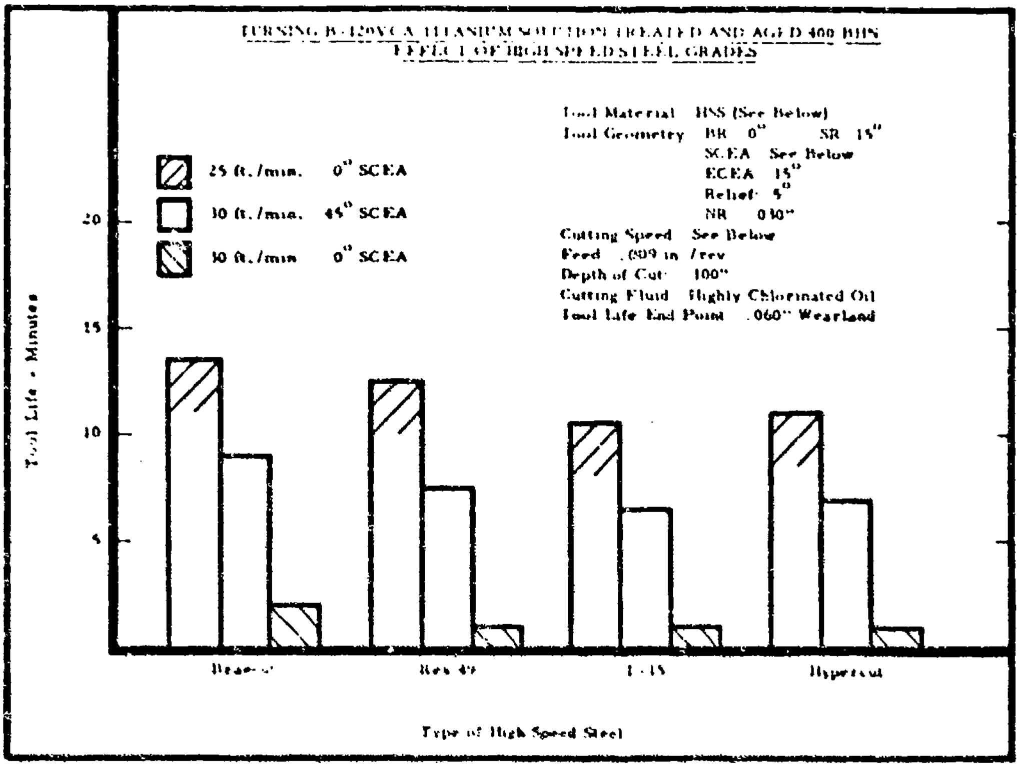


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Figure 171

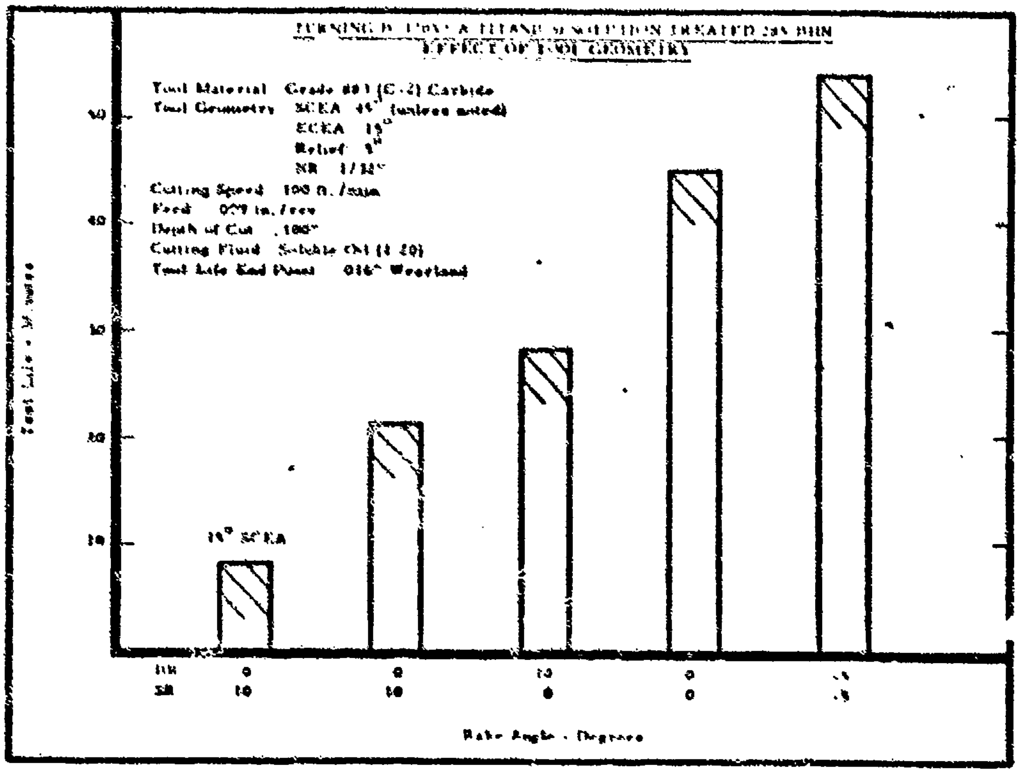

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Figure 172

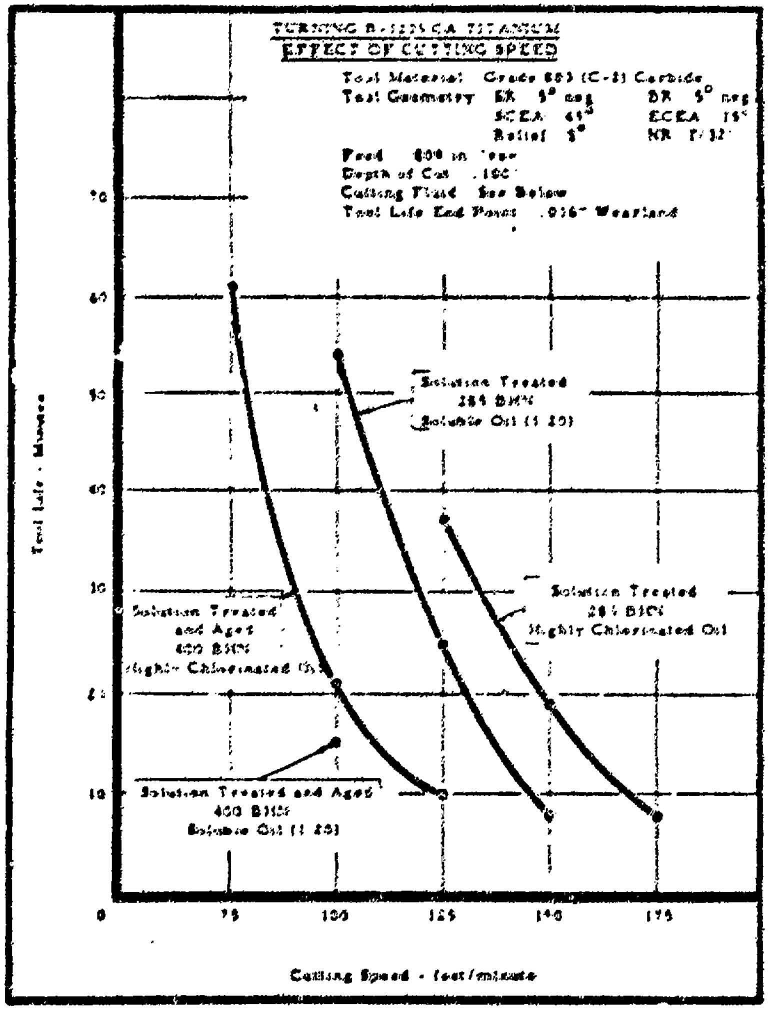

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Figure 173

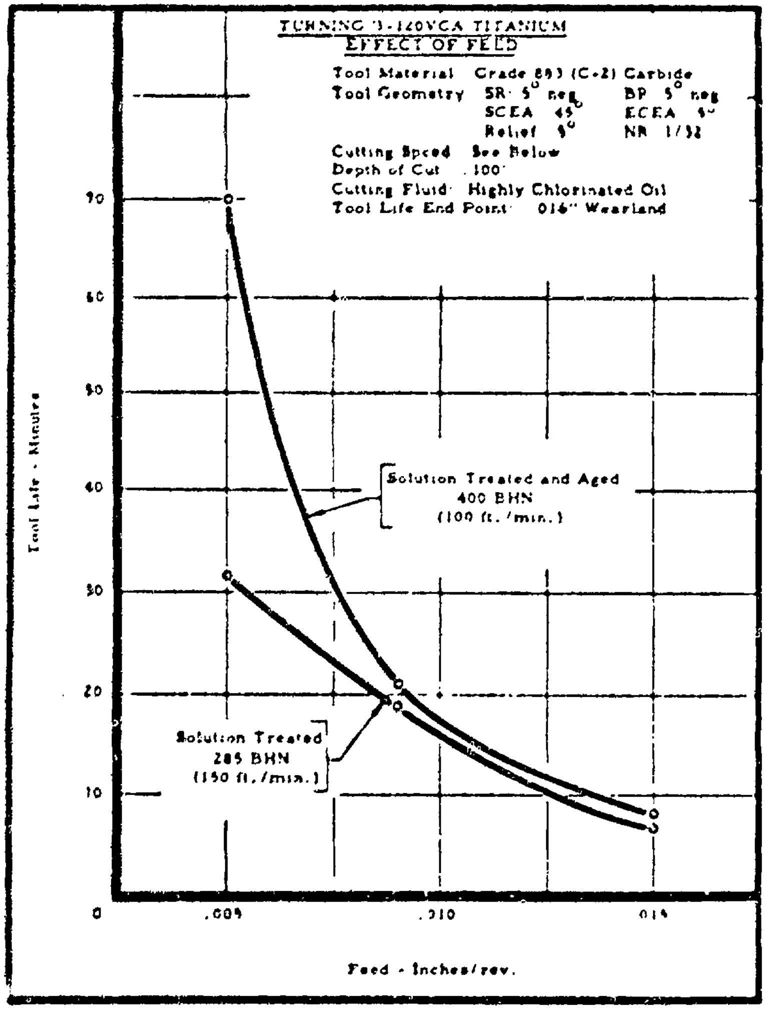

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Figure 174

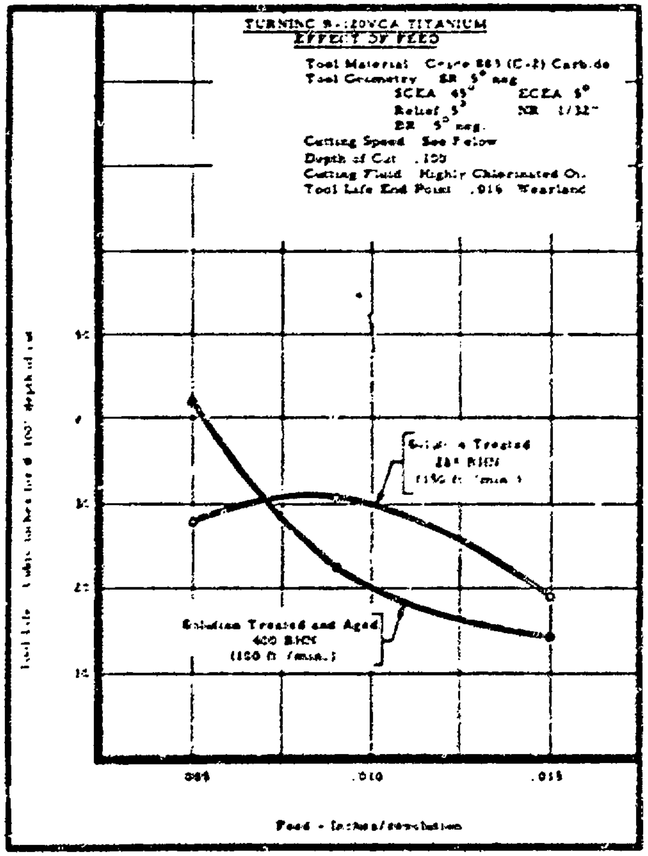

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Figure 175

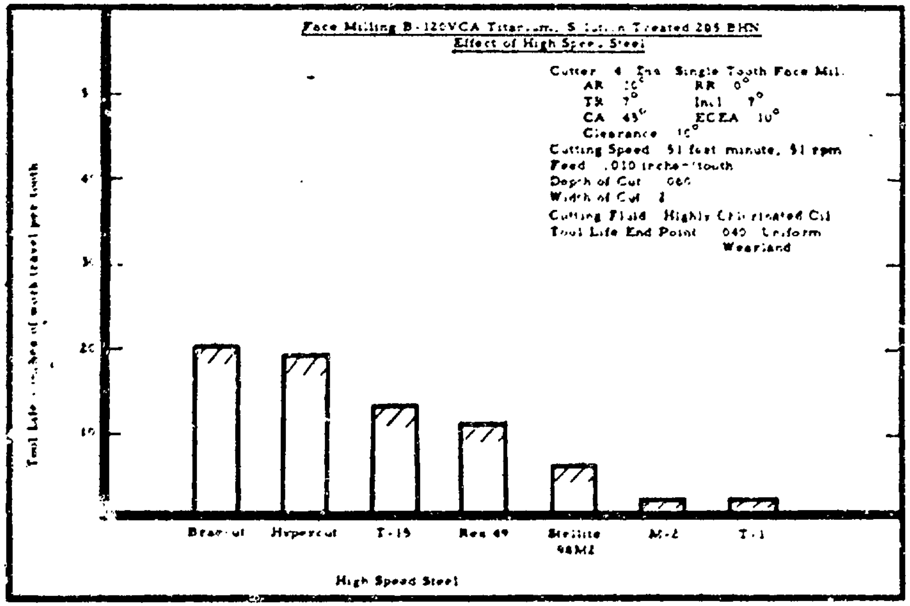

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Figure 176

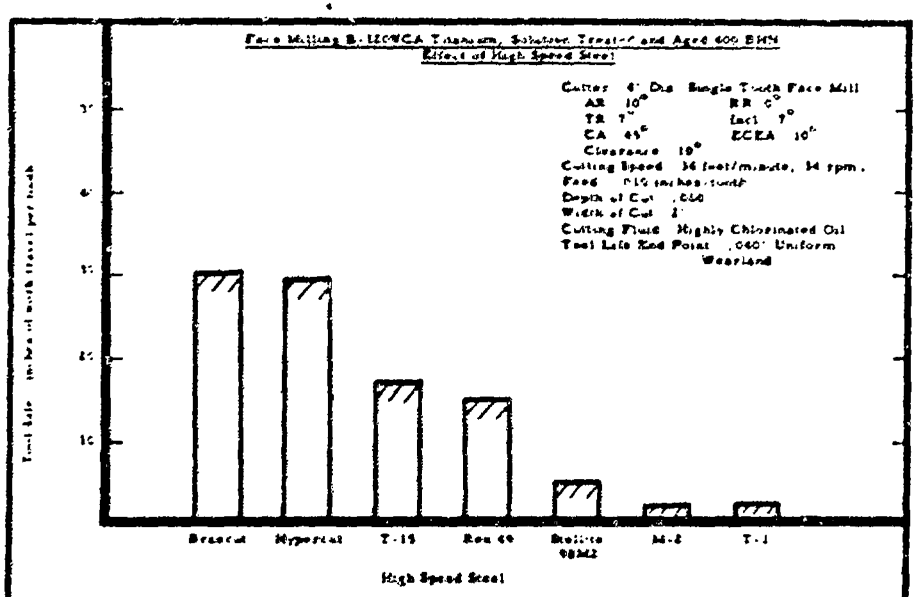

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Figure 177

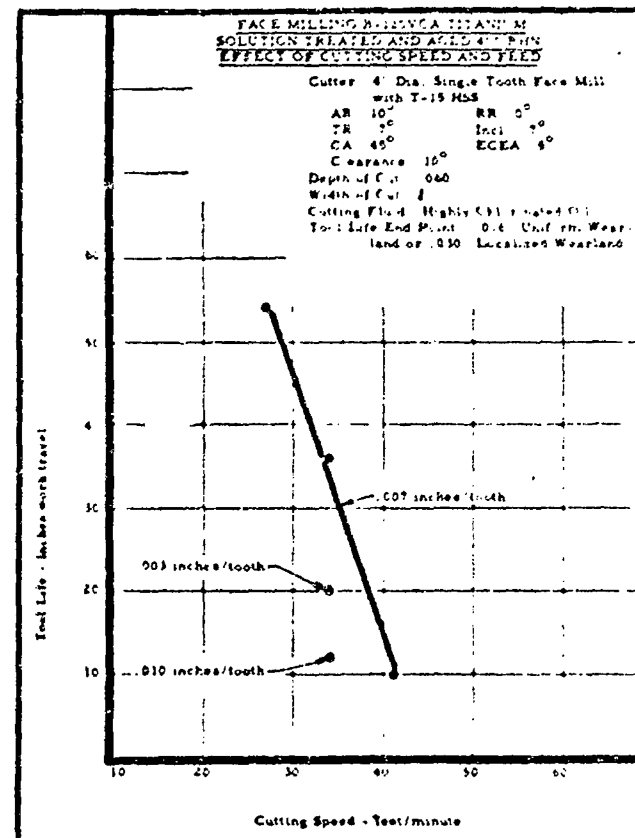

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Figure 178

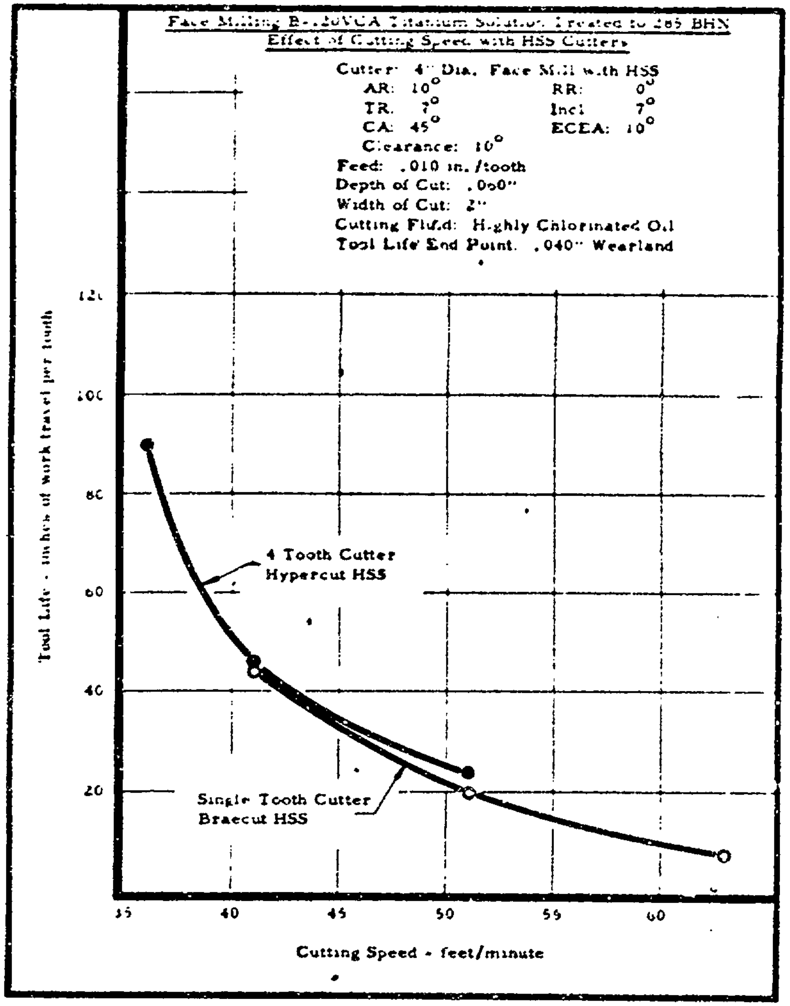

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Figure 179

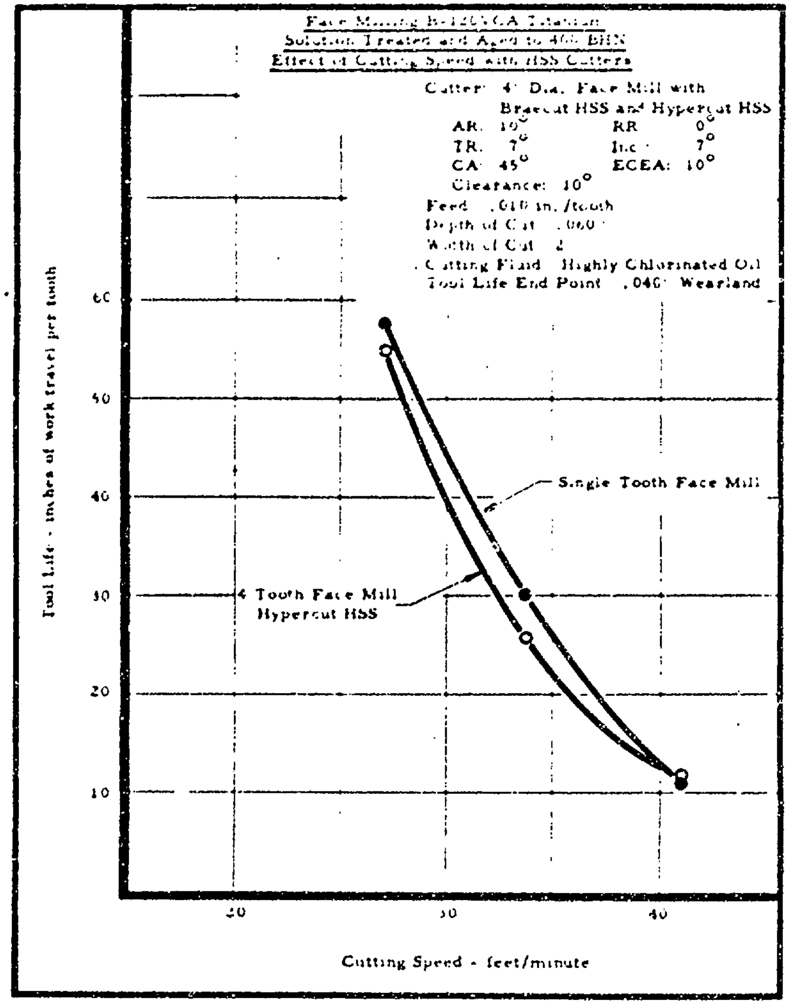

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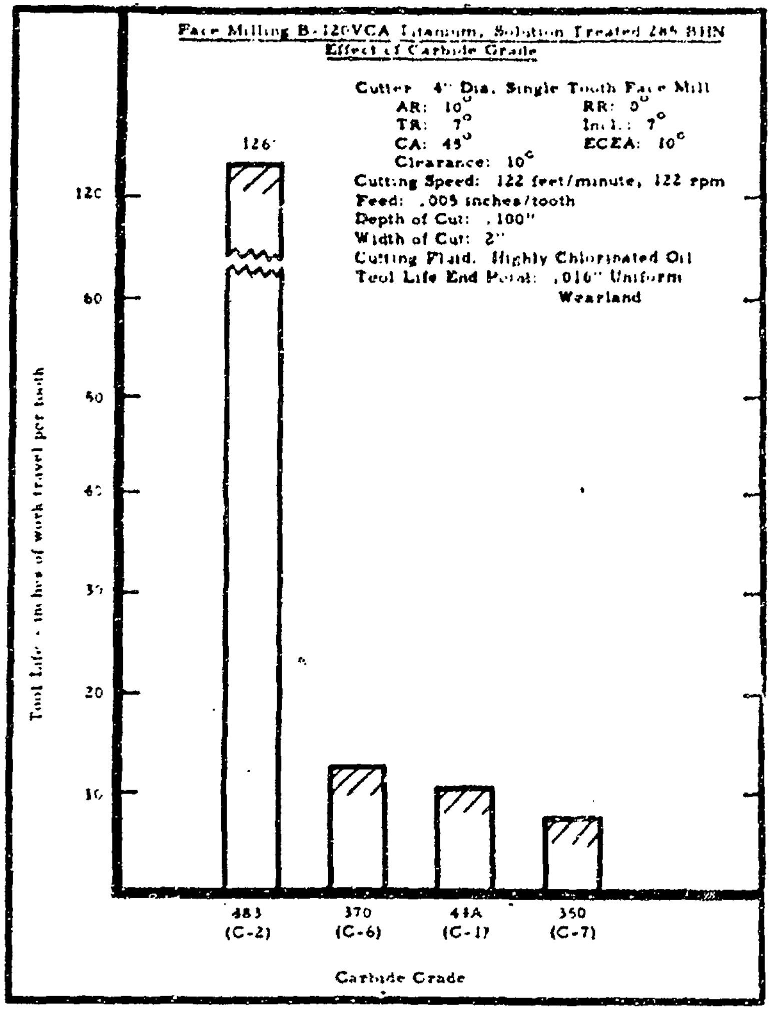
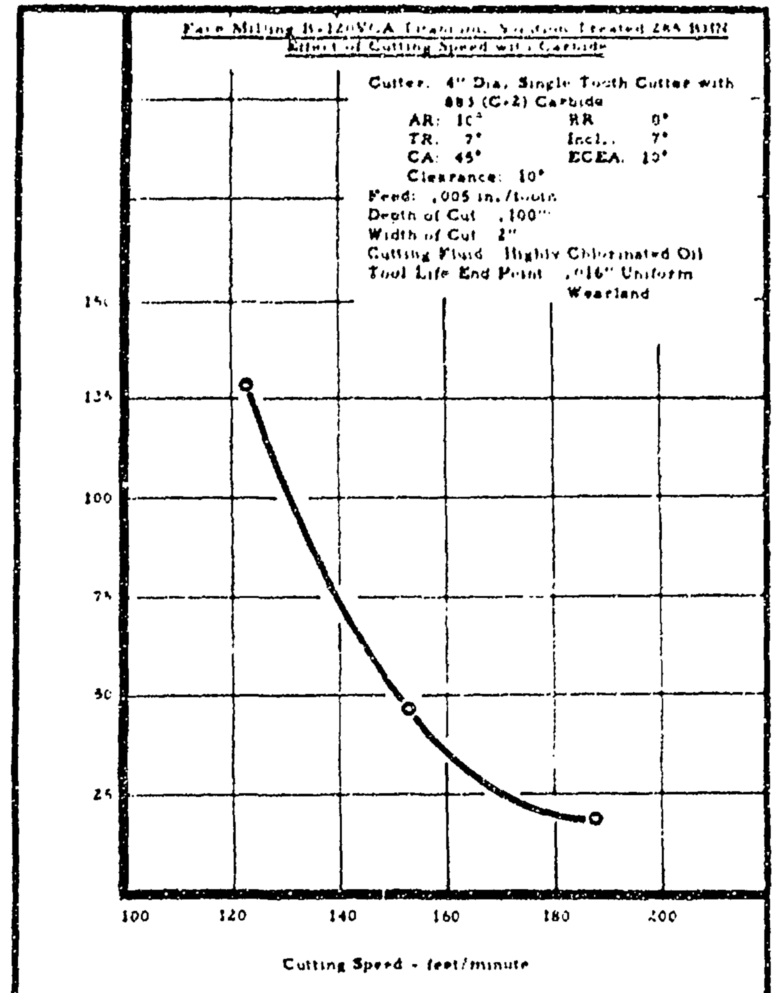
Figure 180



See Text page 157 Figure 161



See Text, page 142 Figure 162

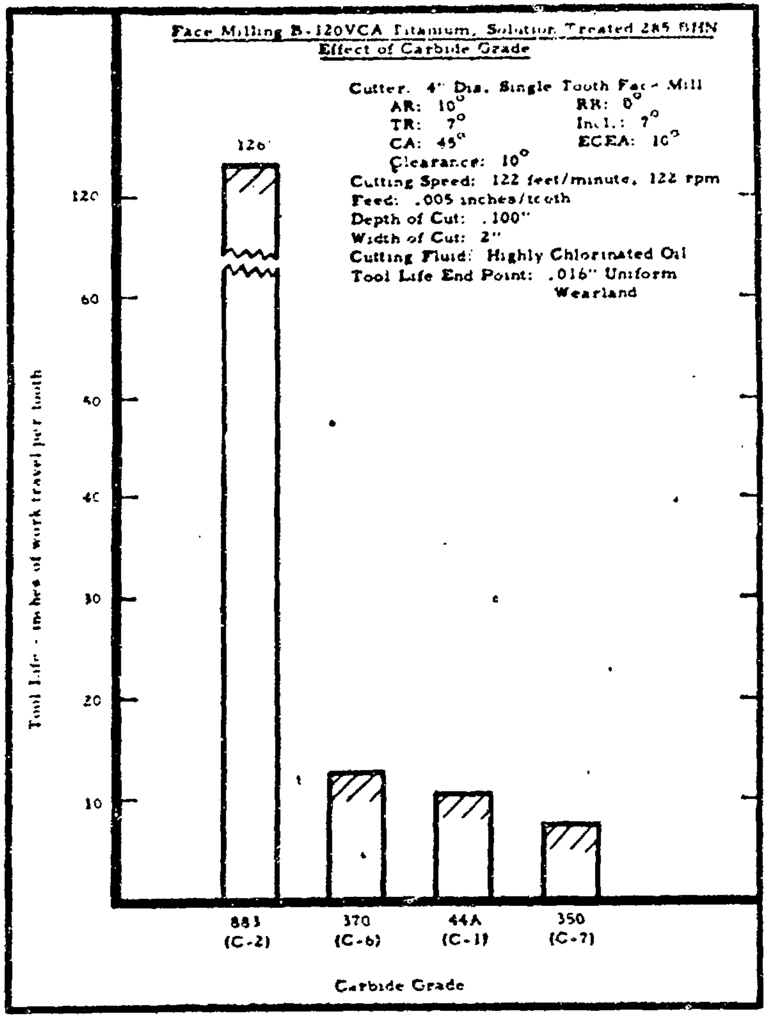


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Figure 181

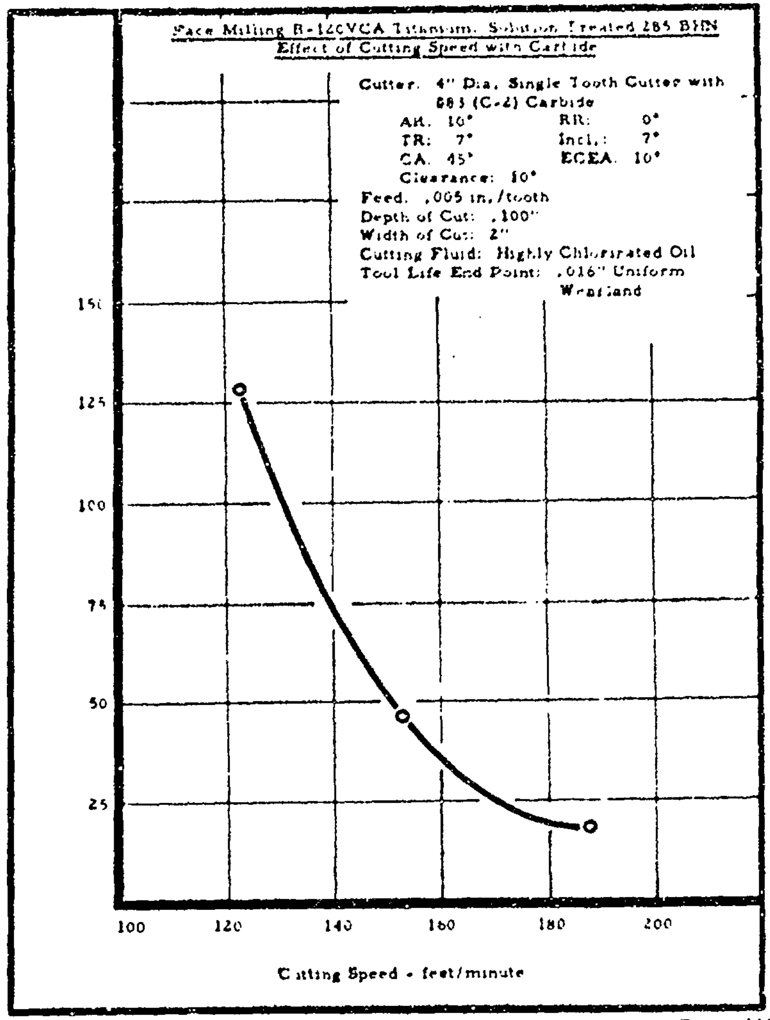

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Figure 182

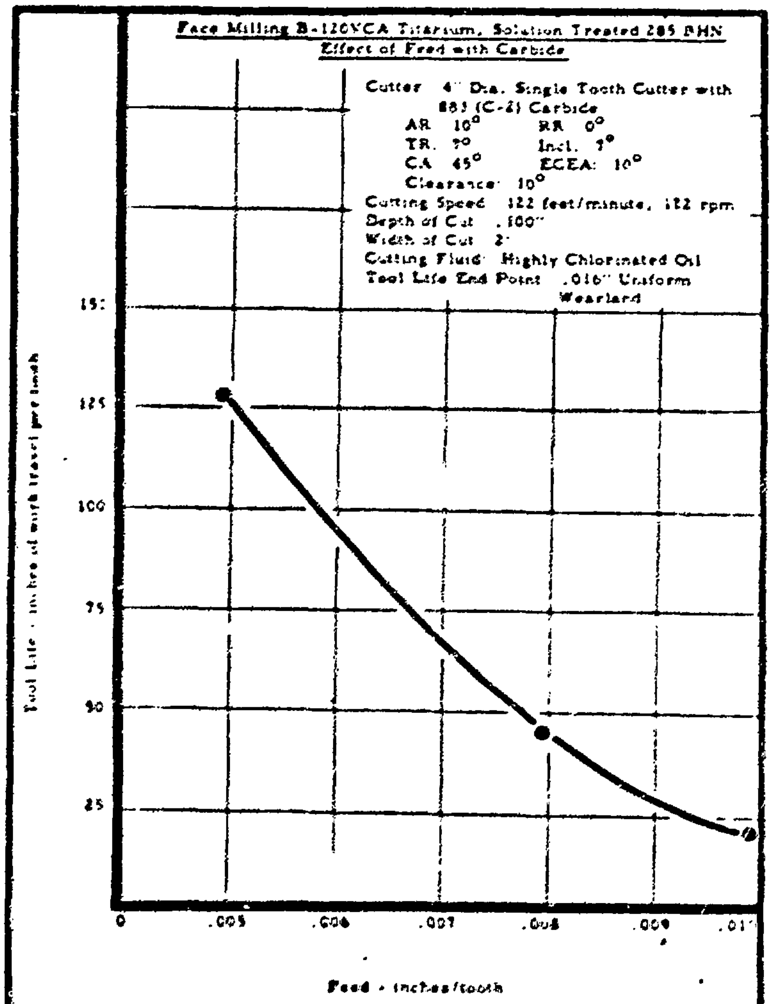

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Figure 183

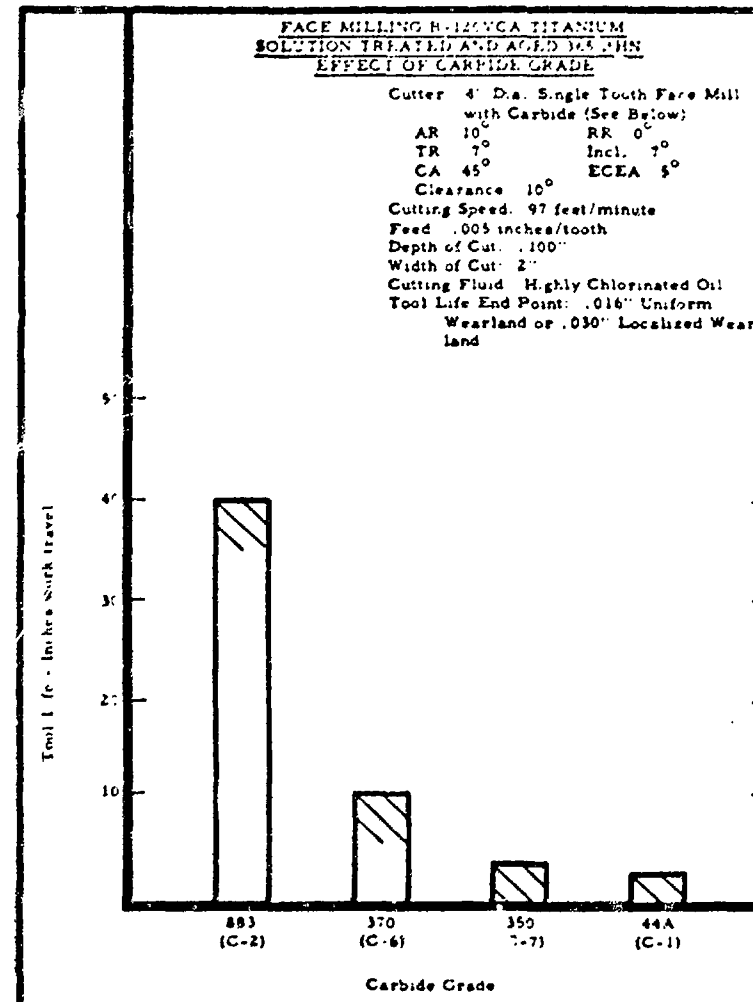

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Figure 184

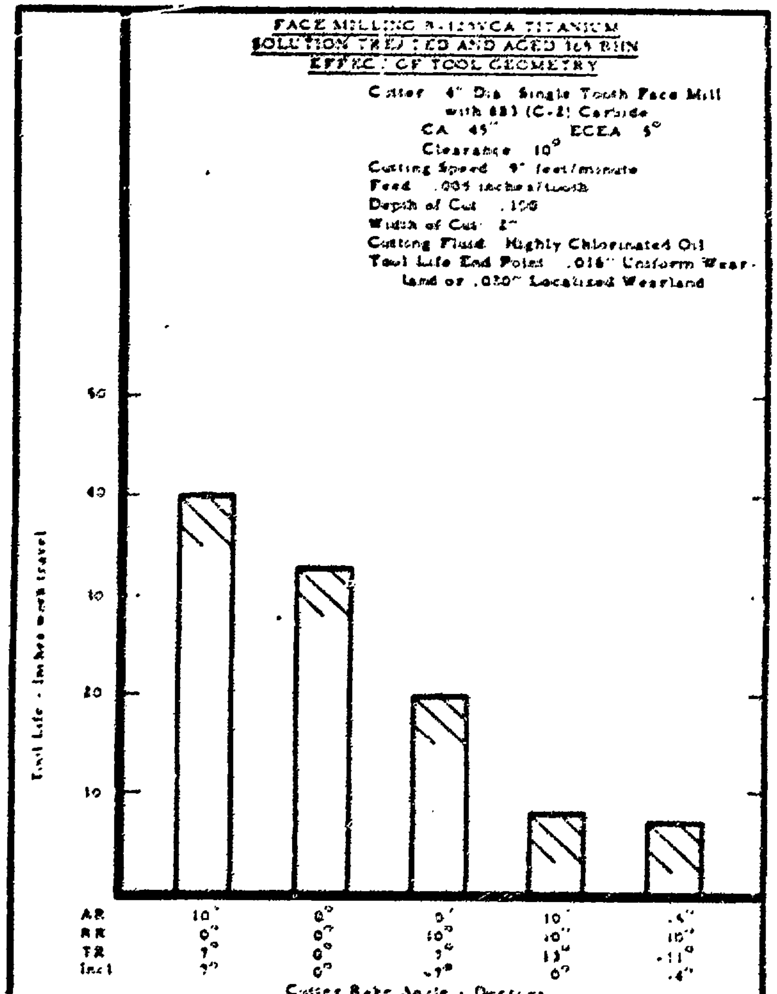

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Figure 185

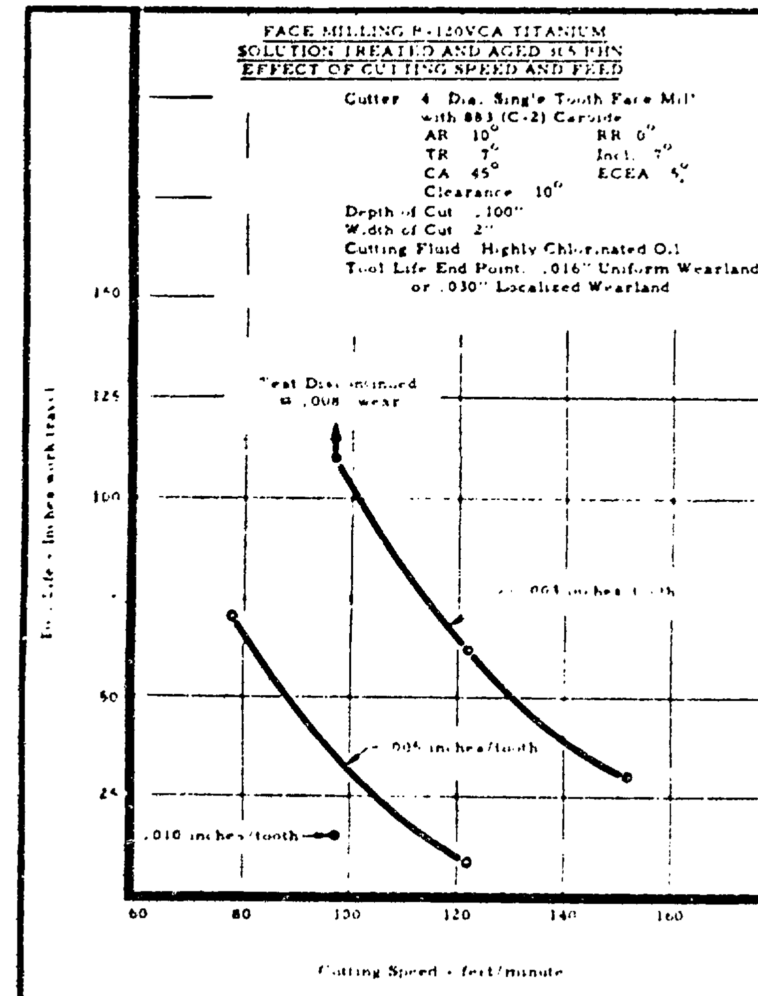

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Figure 186

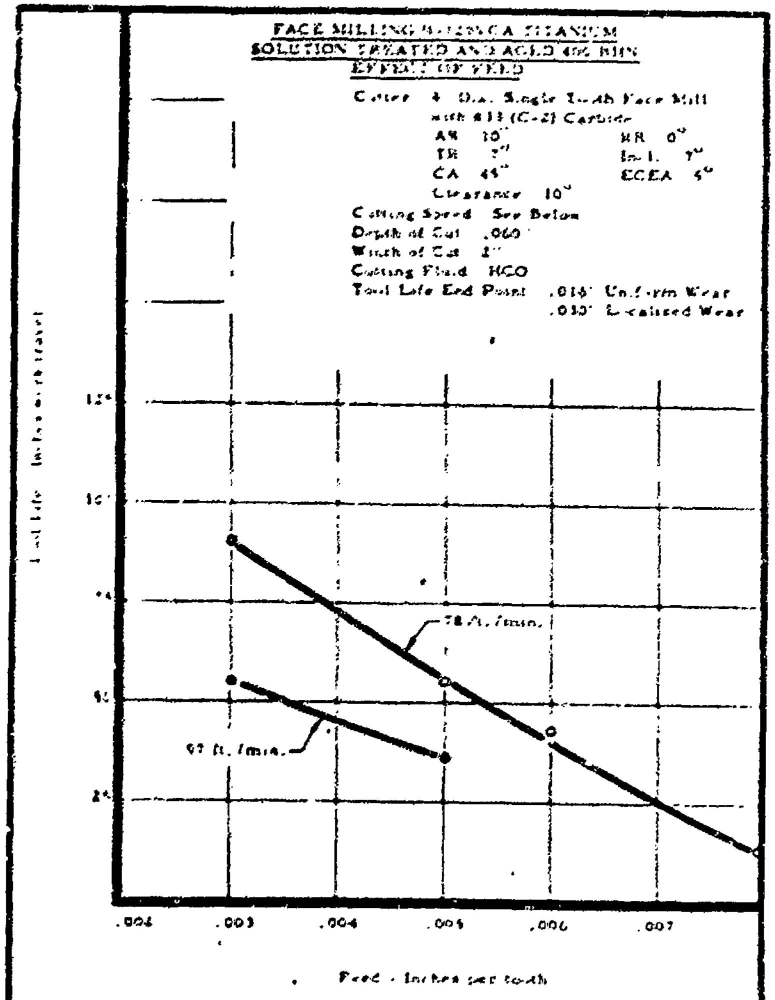

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Figure 107

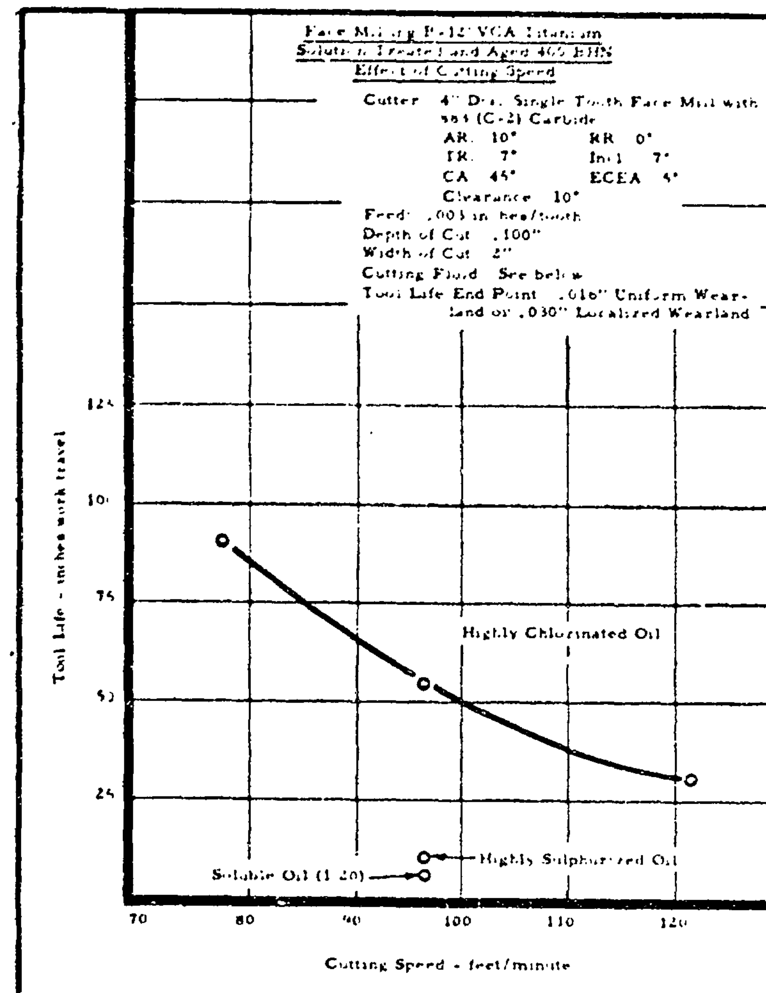

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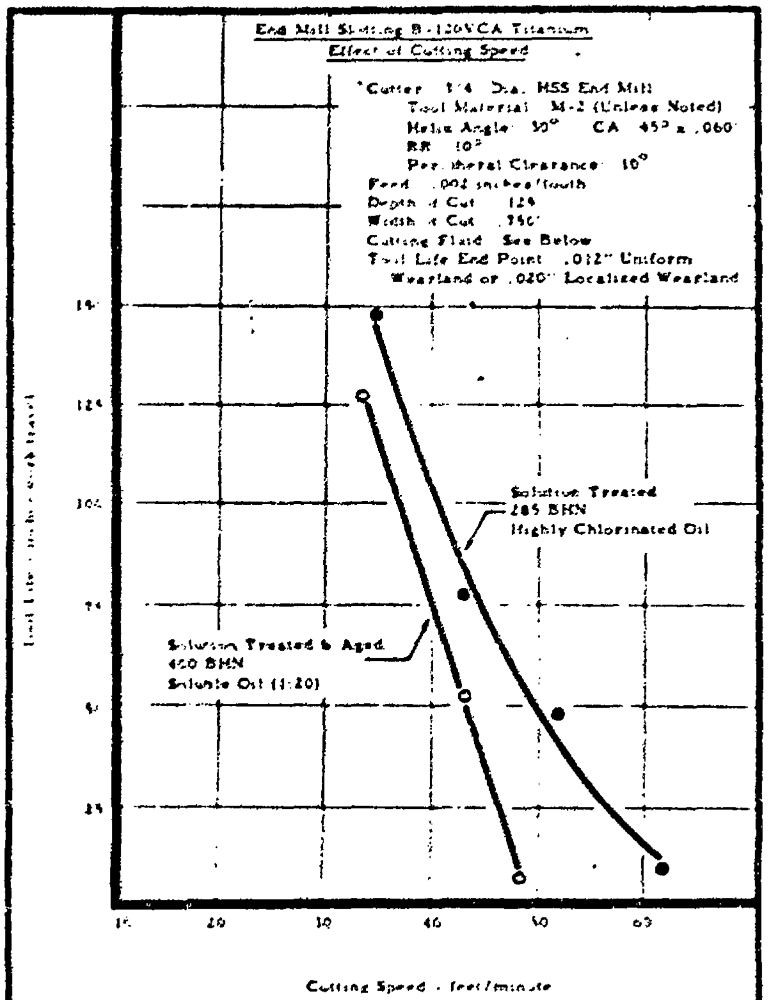
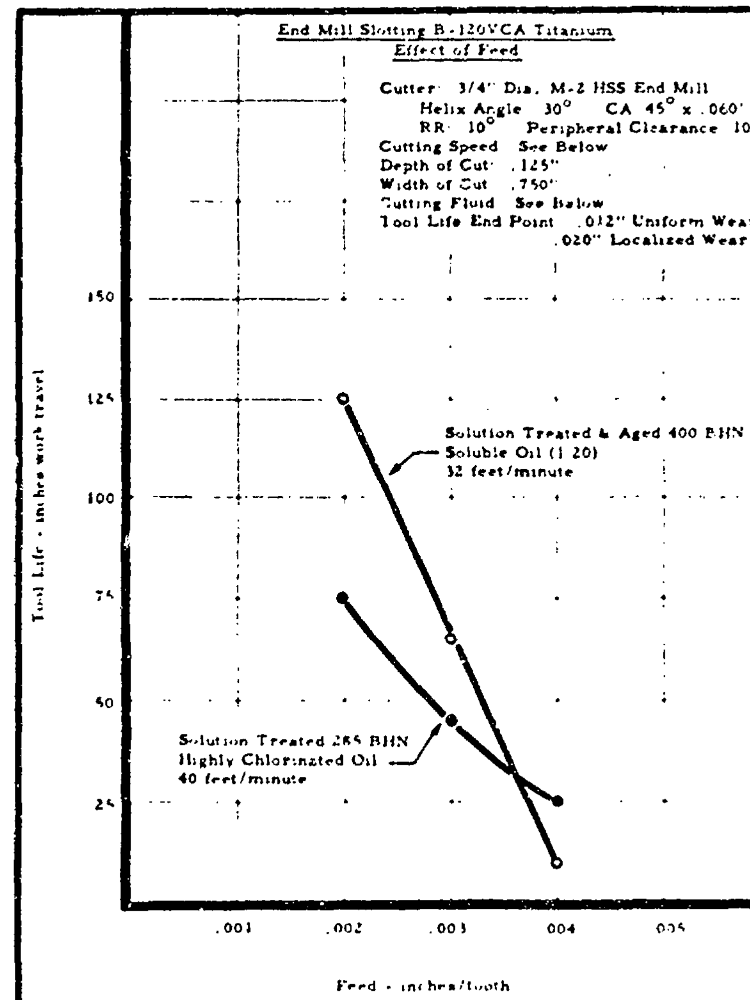
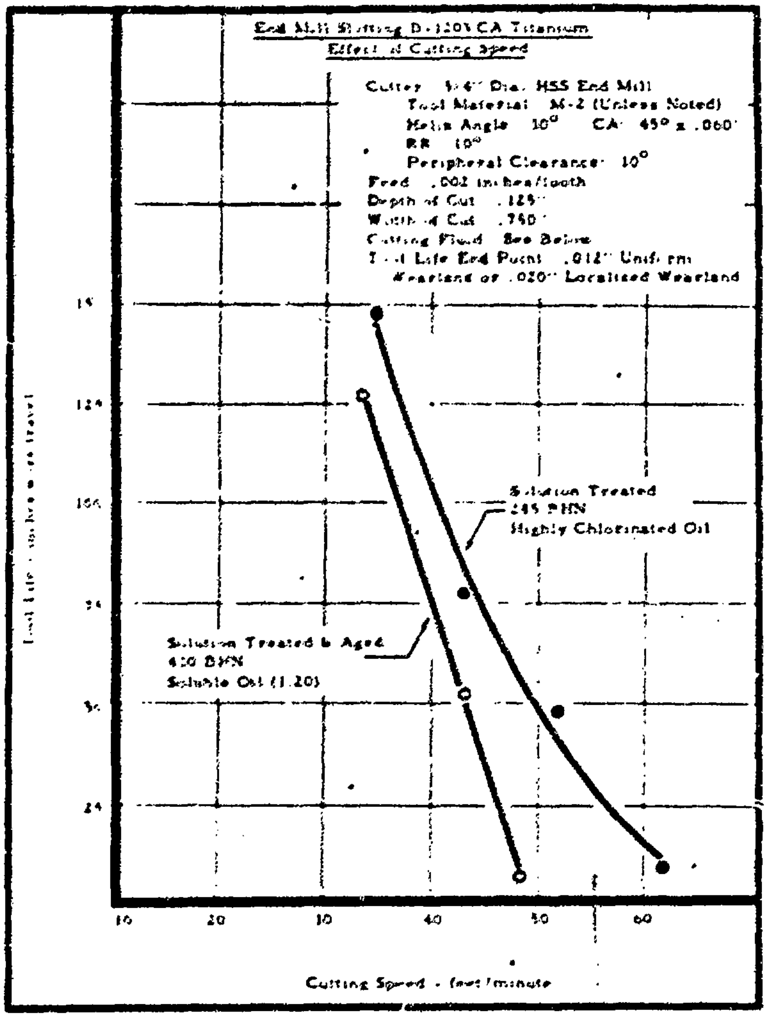
Figure 108



See Text page 143 Figure 189

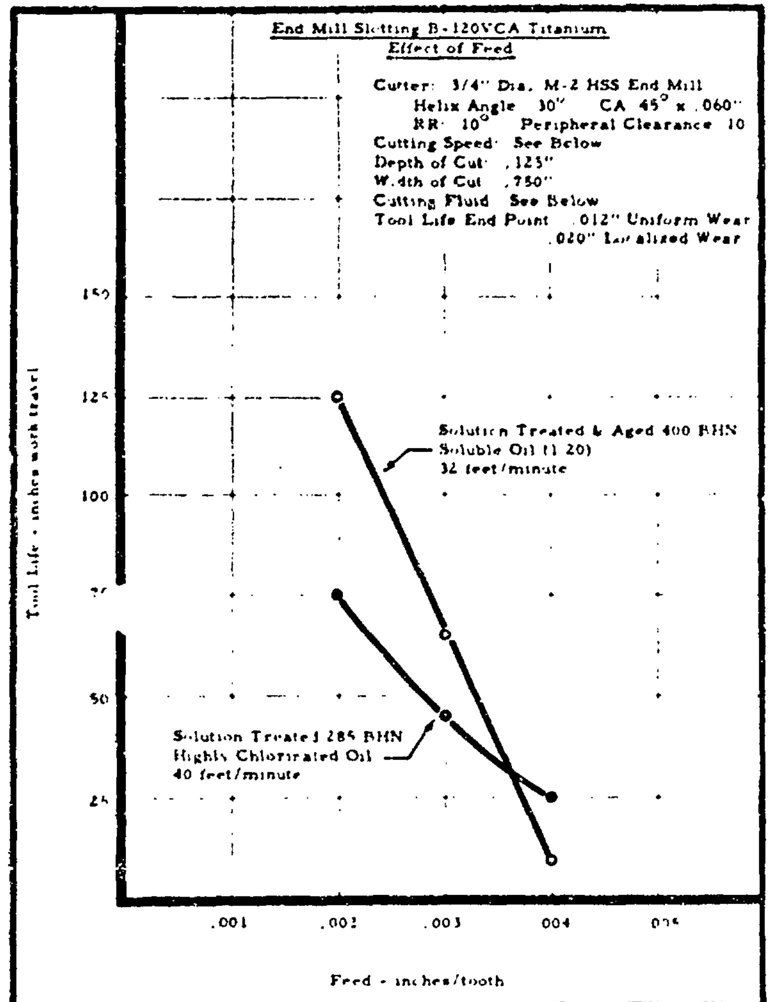


See Text page 143 Figure 190



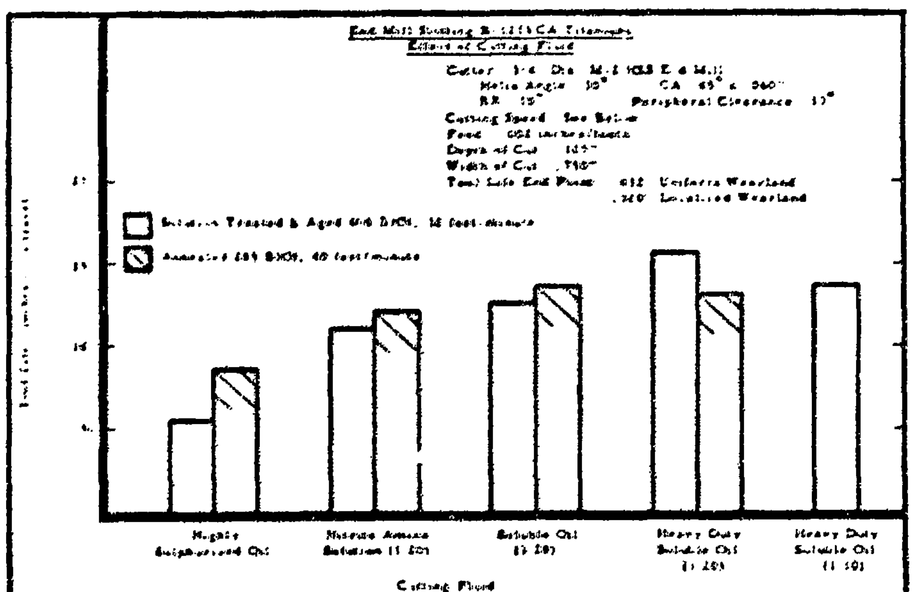
See Text page 143

Figure 139



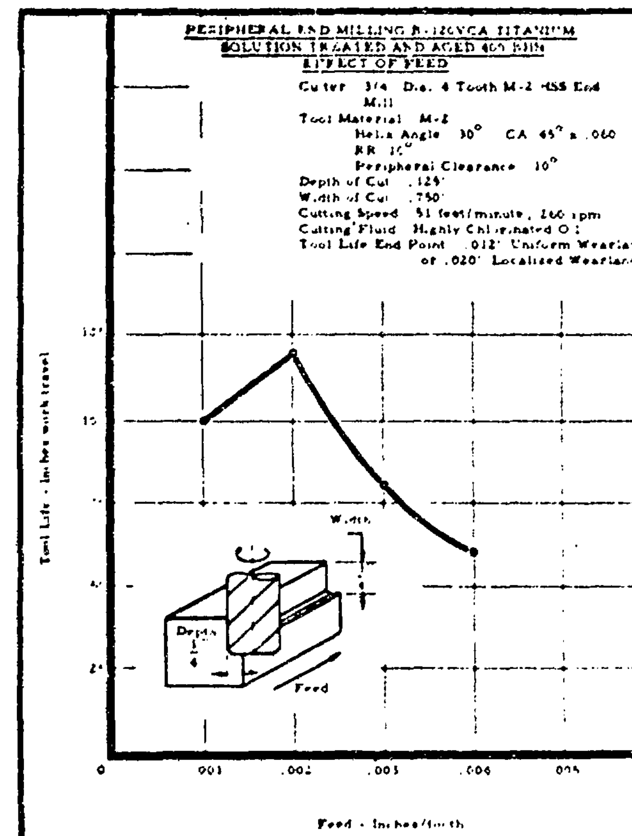
See Text page 143

Figure 140



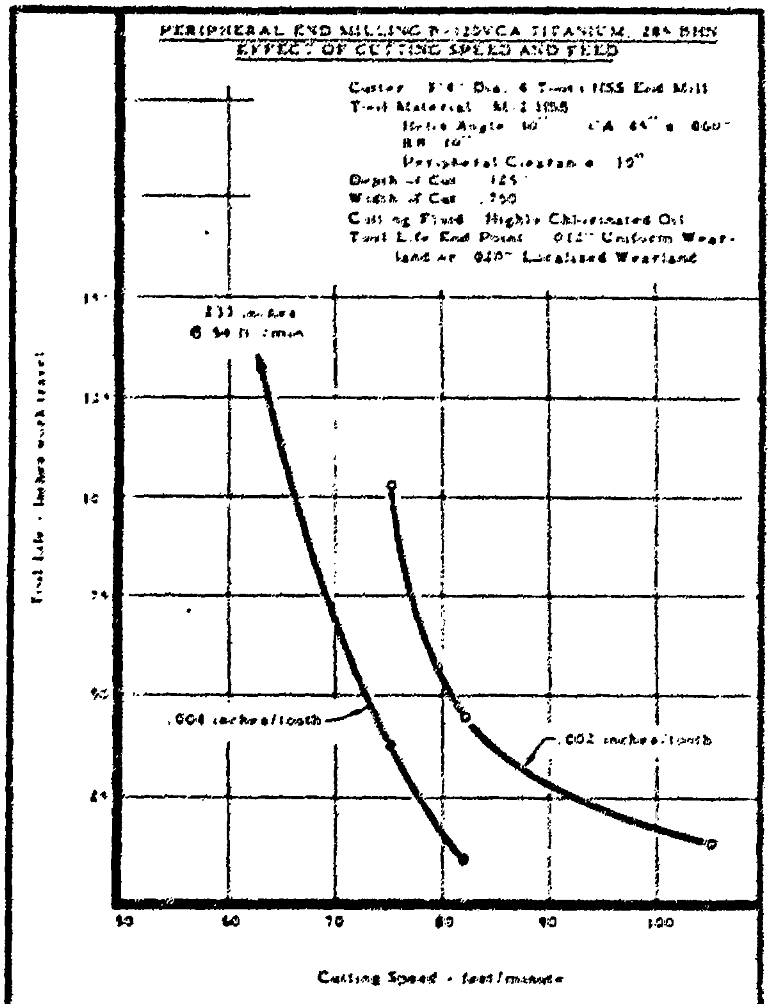
See Text, page 143

Figure 191

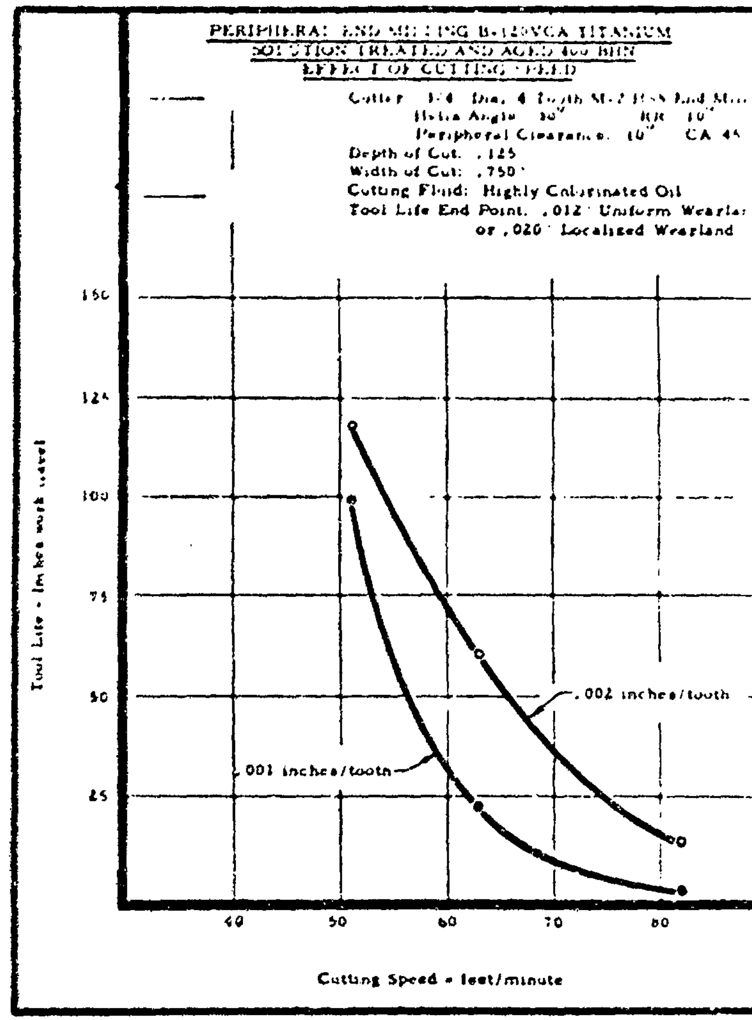


See Text page 143

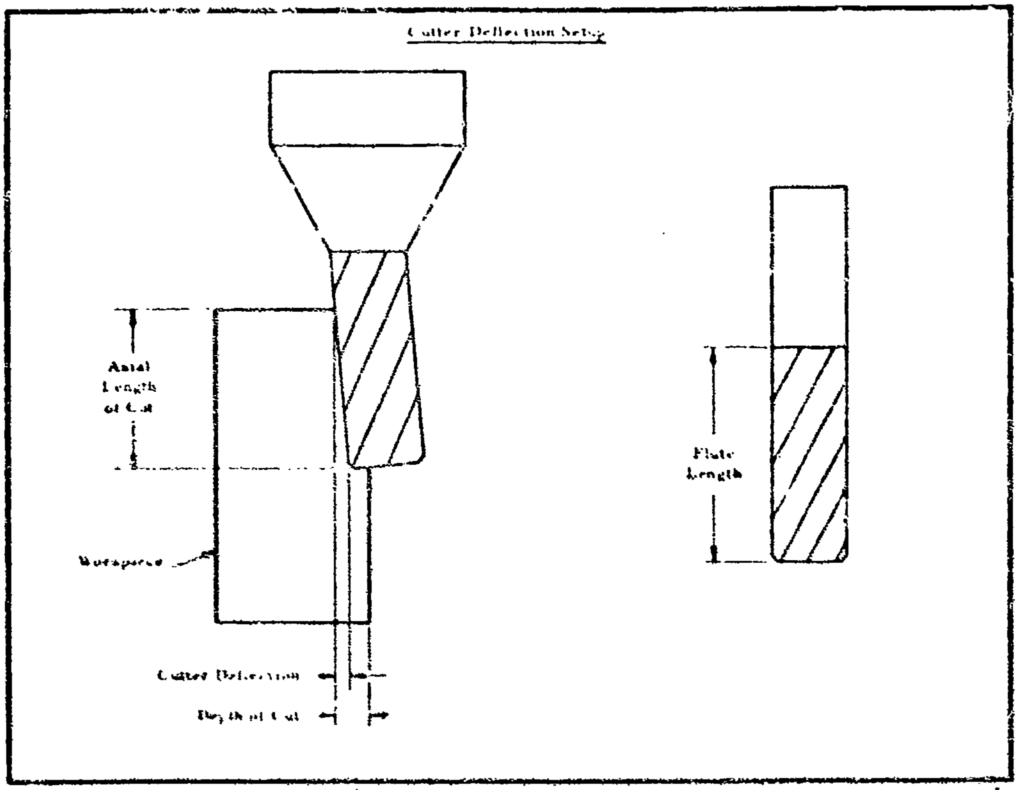
Figure 192



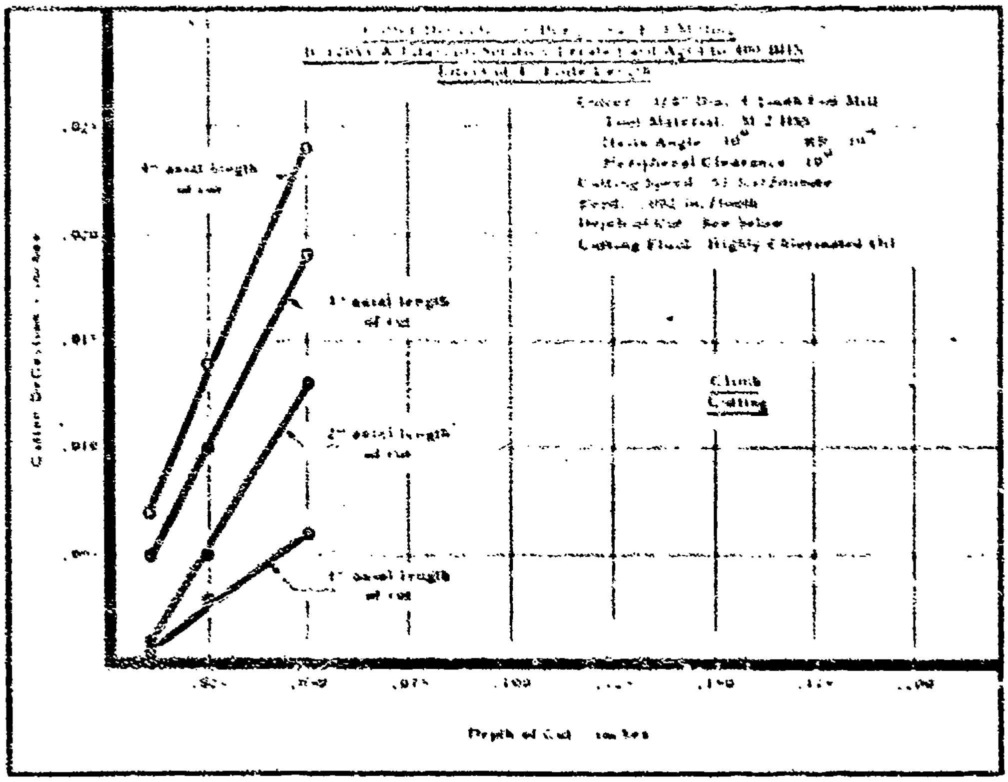
See Text page 141 Figure 193



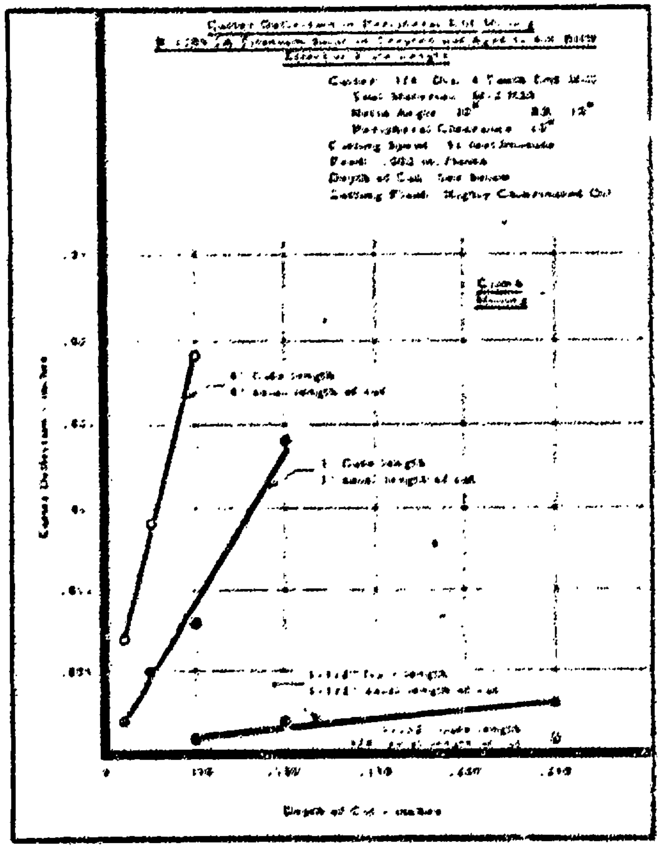
See Text page 143 Figure 194



See Text page [illegible] Figure [illegible]

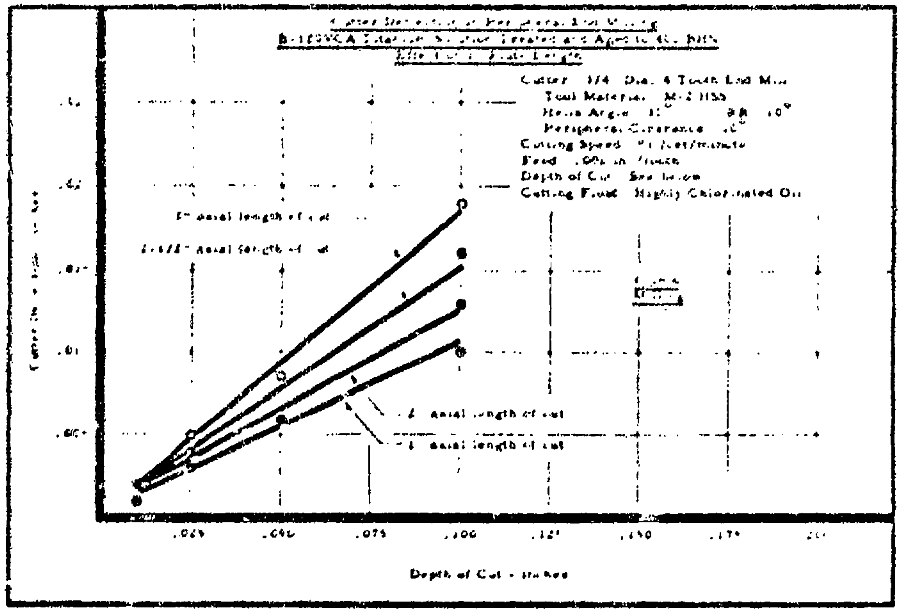


See Text, page 144 Figure 196



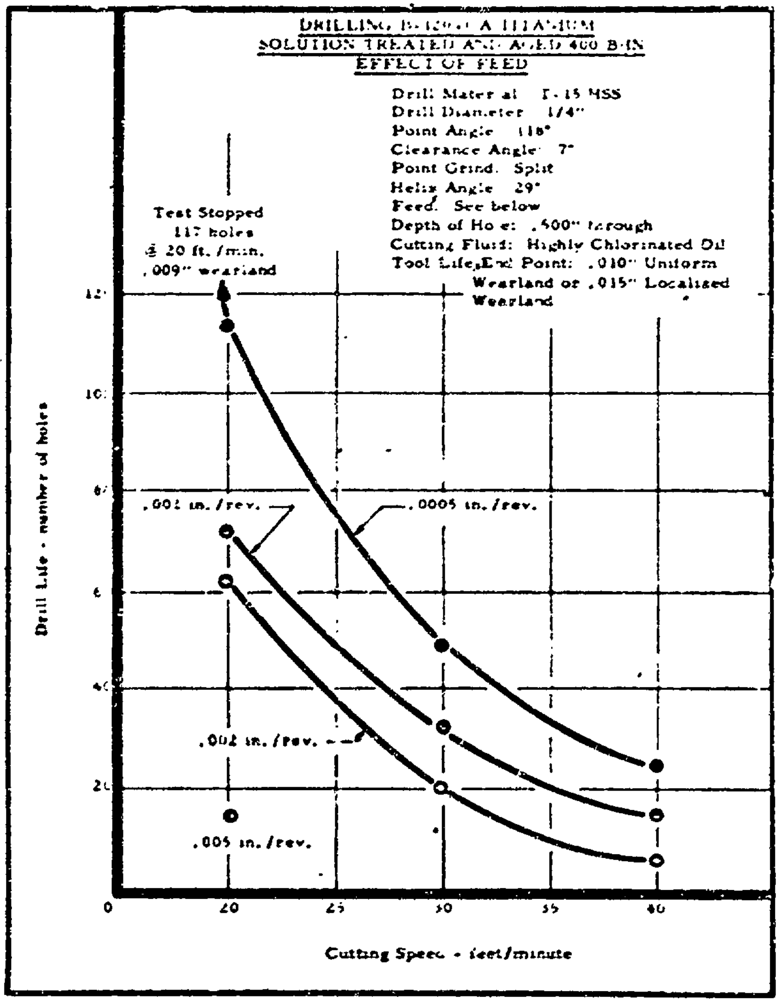
See Text, page 164

Figure 197



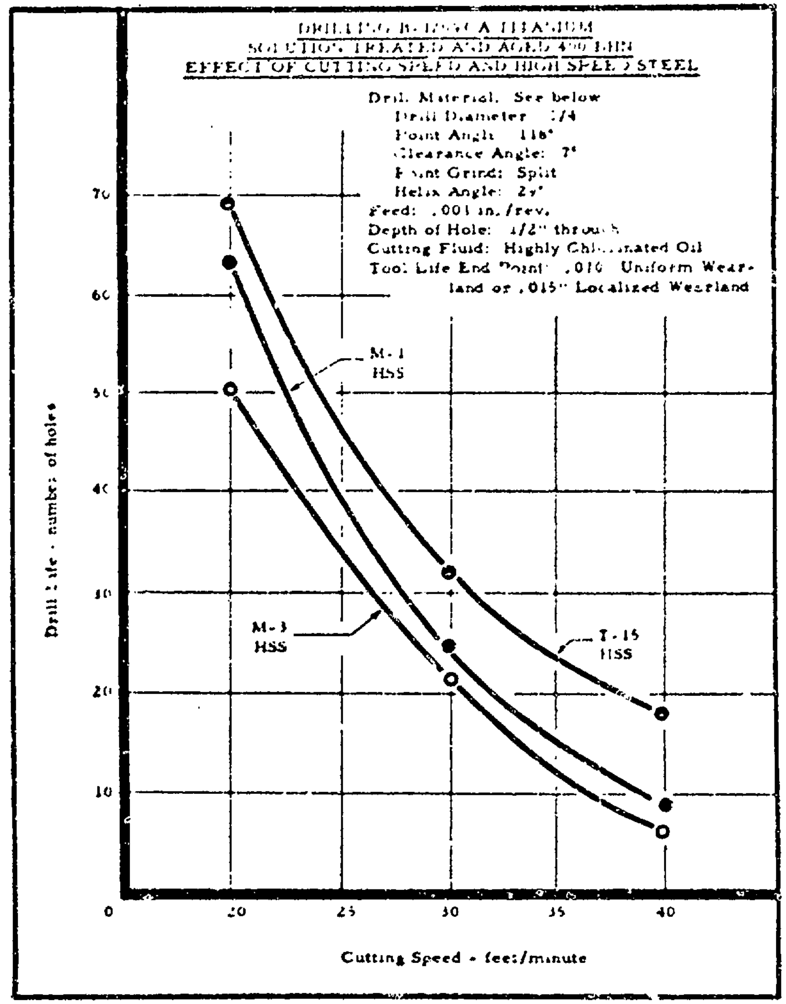
See Text, page 164

Figure 198



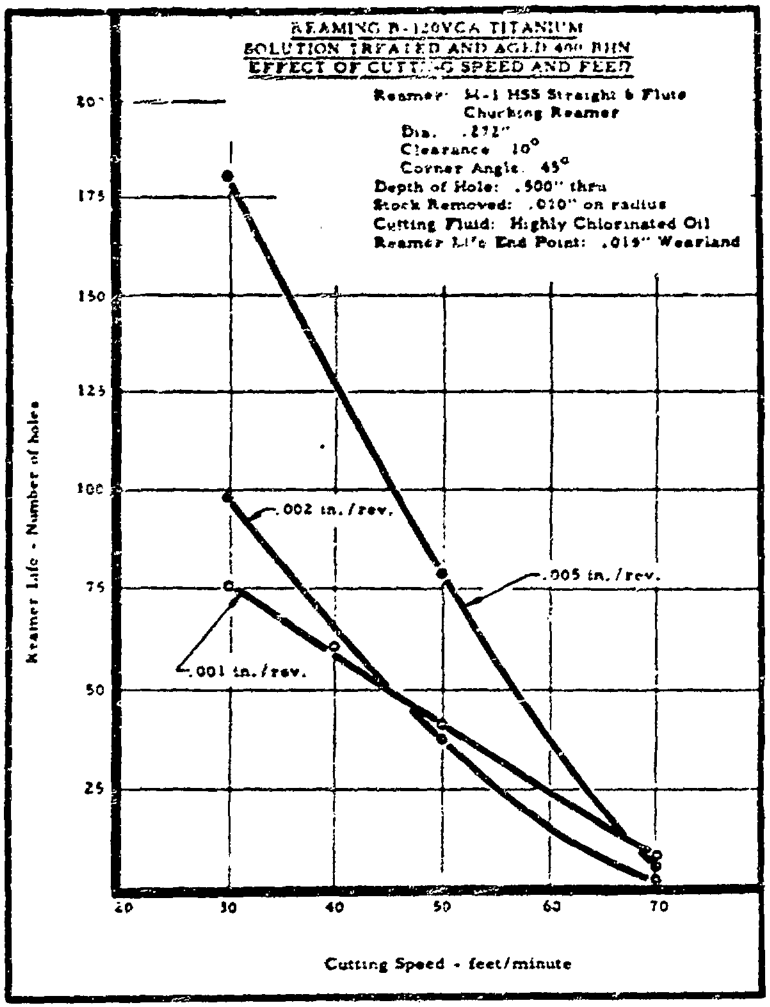
See Text, page 144

Figure 199



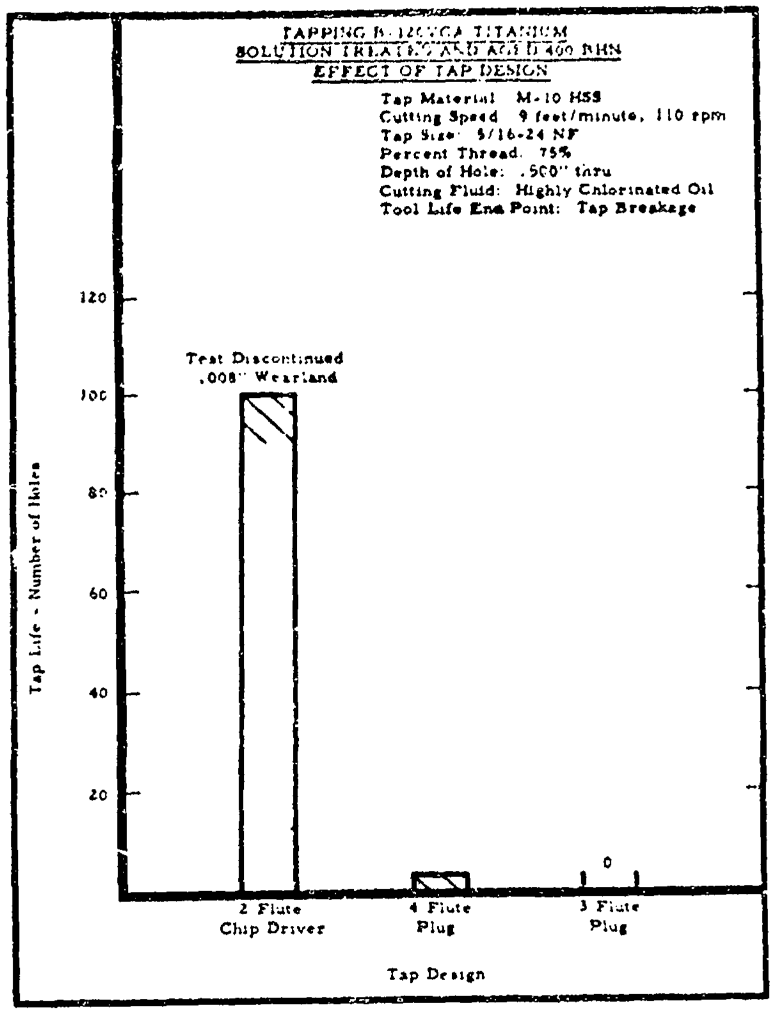
See Text, page 144

Figure 200



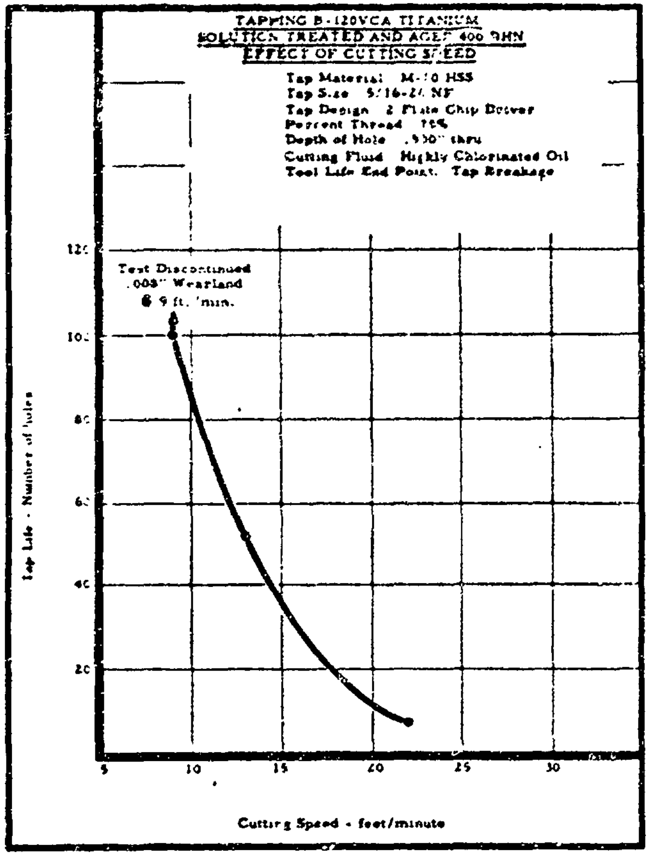
See Text page 144

Figure 201



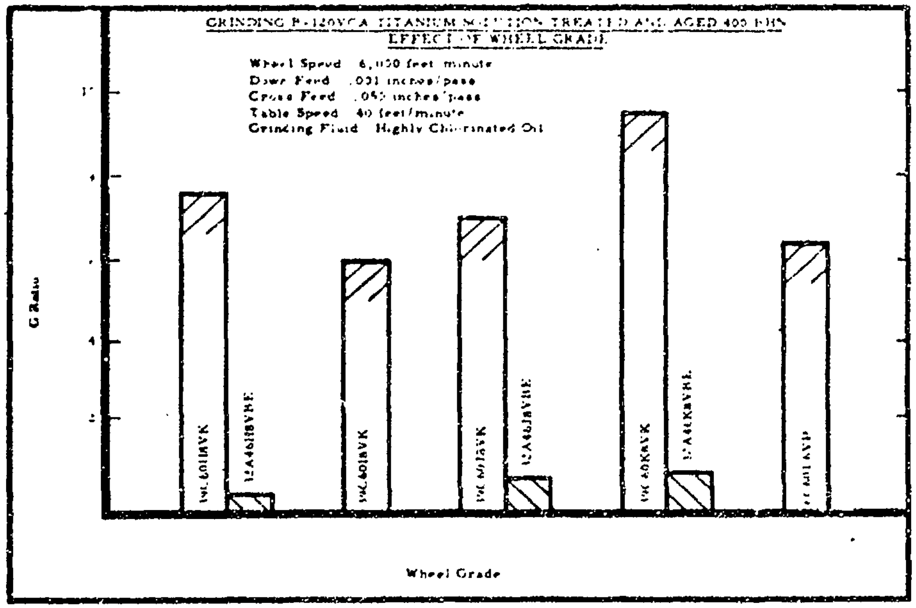
See Text page 144

Figure 202



See Text page 144

Figure 203



See Text, page 145

Figure 204

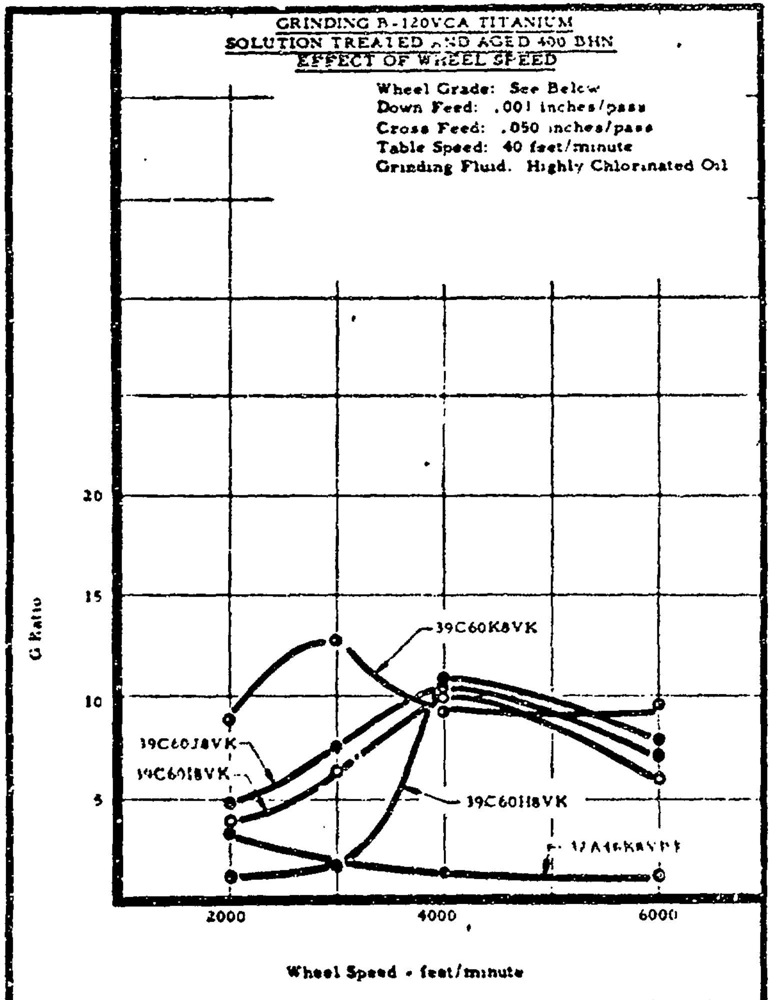


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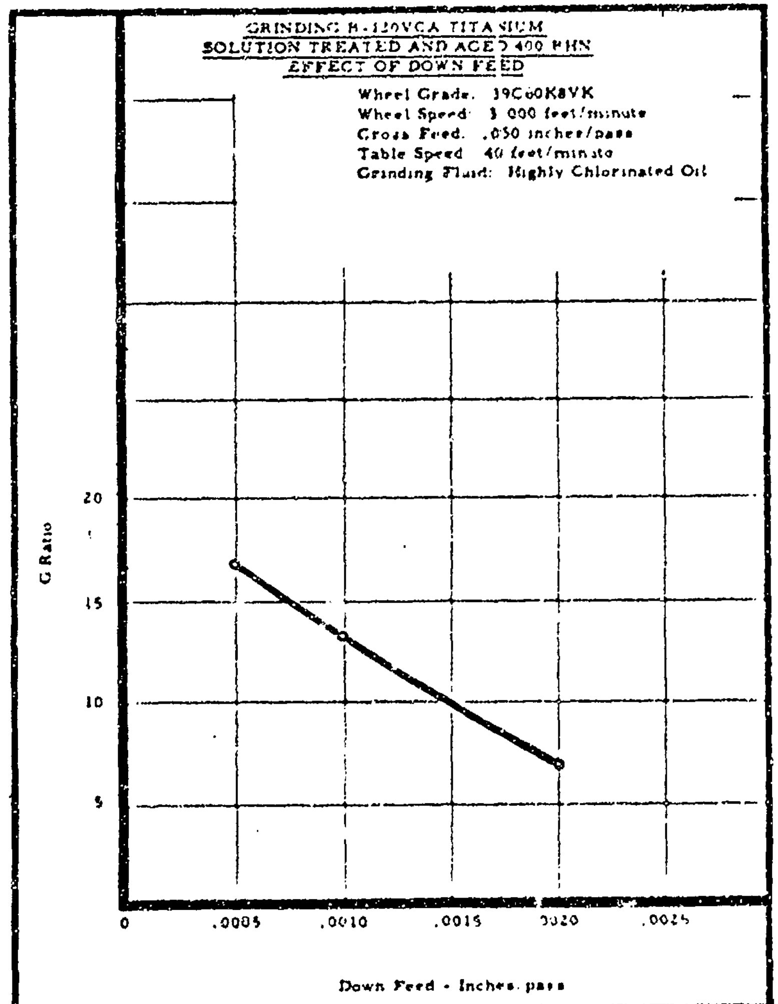
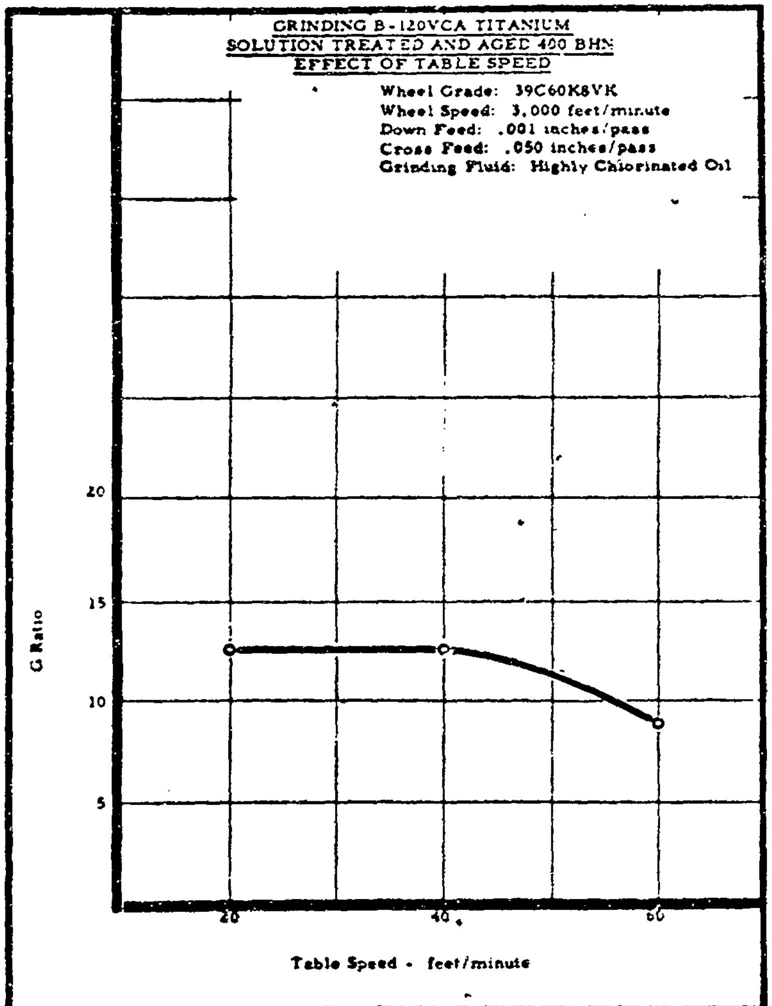
Figure 205

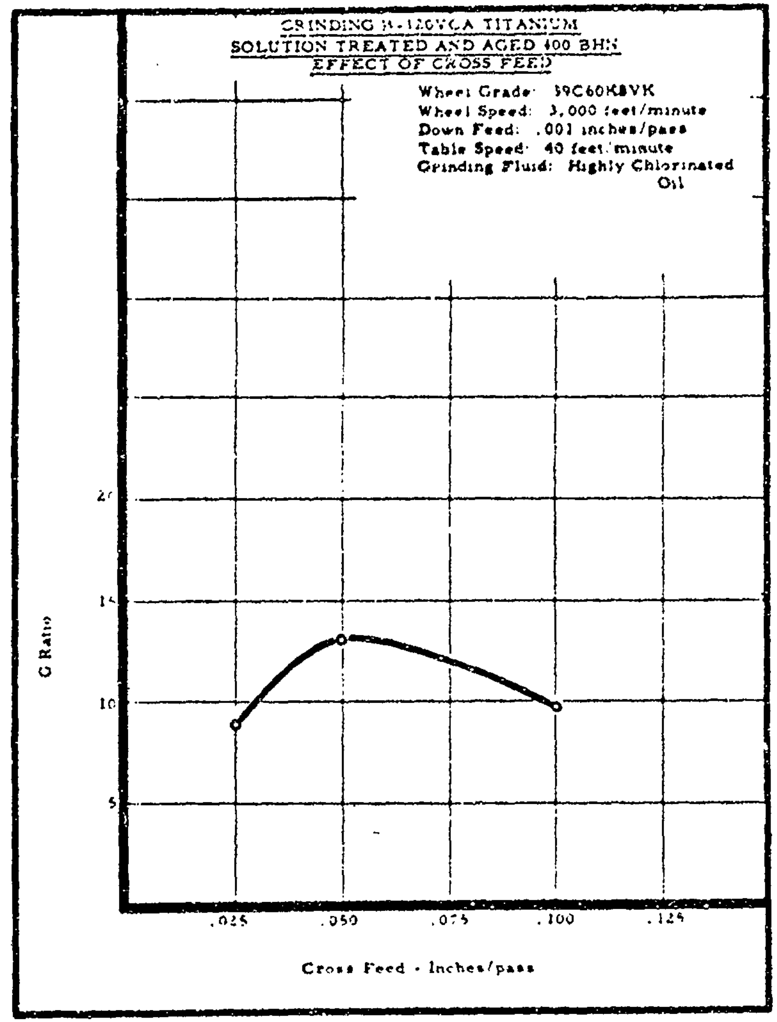


See Text page 145

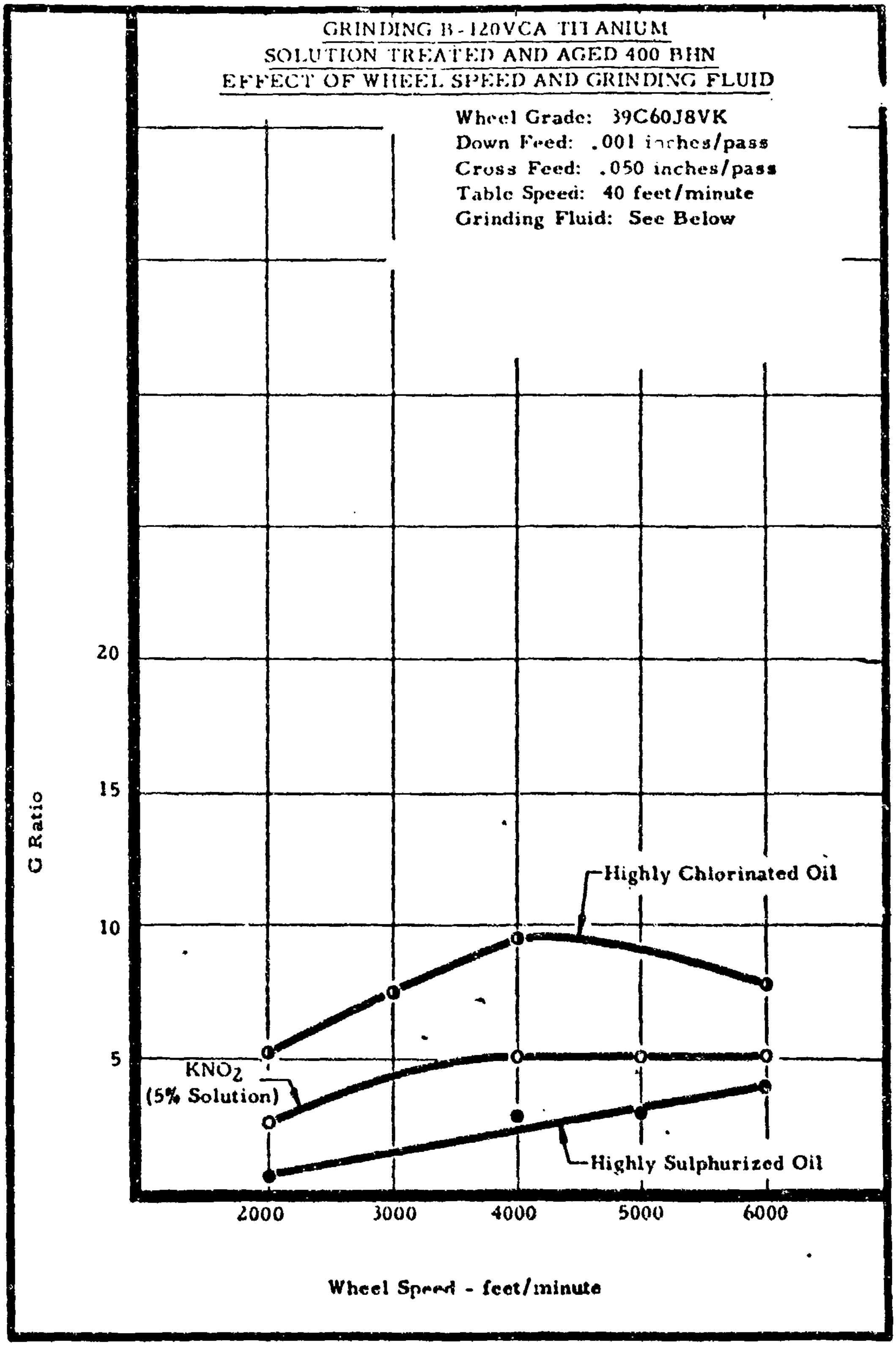
Figure 206



See Text page 145 Figure 207



See Text page 145 Figure 208



See Text page 146

Figure 209

IX. MACHINING RENE 41 HIGH TEMPERATURE ALLOY

Rene 41 is a precipitation hardening nickel base alloy possessing outstanding strength in the 1200 to 1800°F temperature range. It was designed as a forging alloy and is also being used in increasing quantities in sheet form. The high temperature strength of Rene 41 makes it useful for jet engine and high speed airframe components such as after burner parts, turbine castings and buckets, and high temperature panels, vanes, bolts and fasteners.

Rene 41 is normally fabricated in the annealed or solution treated condition which is its most ductile state. It can be subsequently aged to produce a marked increase in strength and stability, especially at elevated temperatures. Because of frequent need to perform some machining operations on fully heat treated components, both conditions have been studied in this program. The solution heat treatment used was as follows: 1975 $\pm$ 25°F for one hour, water quench. The aged Rene 41 covered by this report was also given the following aging cycle: 1400 $\pm$ 25°F for 16 hours, air cool.

Microstructures illustrating both conditions are shown in Figure 210, page 180. The analysis of the heat of Rene 41 studied is presented in Table 13, below:

Table 13
Chemical Composition of Rene 41, Percent

	Cr	Co	Mo	Fe	Ti	C	Al	Ni	Average Hardness BHN
Rene 41	19.0	11.0	10.0	5.0	3.0	.10	1.5	Bal	Annealed: 321 Aged: 365

Recommendations for Machining Rene 41

Rene 41 has a marked tendency to work harden. Carbide tooling is generally preferred for turning; high speed steel is sometimes necessary for milling to avoid tooth chipping. In machining this alloy, rigidity of the machining setup is very important. In face milling, a climb cutting condition is preferred, while in drilling power feeds are necessary to obtain reasonable drill life.

The machining data for solution treated Rene 41 and solution treated and aged Rene 41 has been reviewed, and the general recommendations for machining are given in Tables 14 and 15, pages 181 through 184. Table 14 contains the recommendations for machining Rene 41 in the solution treated condition, while Table 15 presents the recommendations for machining Rene 41 in the solution treated and aged condition.

Turning Tests

A comparison is shown in Figure 211, page 185, of positive and negative rake angles in turning solution treated and solution treated and aged Rene 41. For equivalent tool life, the cutting speeds with the positive rake angle were 30% higher than with the negative rake angle. The effect of feed is presented in Figure 212, page 185, in turning the solution treated and aged alloy. It is apparent that the feed should be in the range of .007 to .011 in./rev.

The tool life curves shown in Figure 213, page 186, give a comparison of the tool life data obtained in turning Rene 41 with high speed steel and carbide tools for both the solution treated and the solution treated and aged conditions. The machining conditions represent the best conditions obtained with respect to tool material, tool geometry and cutting fluid. Better tool life was obtained with both T-15 high speed steel and K-6 (C-2) carbide tools for Rene 41 in the solution treated condition, 321 BHN, than in the solution treated and aged condition, 365 BHN.

At a cutting speed of 70 feet/minute, a feed of .009 in./rev. and using a soluble oil cutting fluid, a tool life of approximately 40 minutes was obtained with K-6 carbide in turning solution treated Rene 41. The tool life on the aged Rene 41 for the same cutting conditions was about 25 minutes.

In turning with T-15 high speed steel tools at a cutting speed of 12 feet/minute and a feed of .009 in./rev., tool life was 75 minutes for a wearland of .010" for Rene 41 in the solution treated condition, Figure 213. At the same cutting speed and feed, tool life was 81 minutes for a wearland of .030" for Rene 41 in the solution treated and aged condition. It was necessary to use a highly chlorinated oil as the cutting fluid to obtain the 81 minutes tool life for Rene 41 in the solution treated and aged condition.

Face Milling Tests

The machining data obtained in the face milling tests on Rene 41 solution treated, 321 BHN, and solution treated and aged, 365 BHN, is presented in Figures 214 through 223, pages 186 through 191.

The type T-15 high speed steel tool gave the best tool life, Figure 214, page 186, of all the high speed steel and cast alloy tools tested in face milling aged Rene 41. Tool life was 88 inches of work travel per tooth at 18 feet/minute and at a feed of .011 in./tooth. With a type T-1 high speed steel tool, the tool life was only 41 inches for the same cutting conditions, and only five inches for the cast alloy Stellite 98 M-2 tool.

The effect of feed in face milling with high speed steel tools is shown in Figure 215, page 187. At a cutting speed of 27 feet/minute, tool life in face milling with high speed steel tools is about the same for feeds from .005 to about .011 in./tooth, after which it drops off rapidly.

Face Milling Tests (continued)

Figure 216, page 187, shows the tool geometry evaluation for high speed steel cutters in face milling aged Rene 41. The best geometry was an axial rake of 0° and a radial rake of 30°, with a 45° corner angle. This tool geometry provided a tool life of 75 inches work travel per tooth at a cutting speed of 22 feet/minute and a feed of .010 in./tooth using a highly chlorinated oil cutting fluid.

A comparison of the tool life obtained in face milling solution treated Rene 41 at 321 BHN and solution treated and aged Rene 41 at 365 BHN with high speed steel tools is shown in Figure 217, page 188. The solution treated Rene 41 shows better face milling characteristics than the aged Rene 41 when milling with the high speed steel cutters. The tool life for the solution treated Rene 41 was 80 inches of work travel per tooth. In this case, the test was stopped after .012" wear had developed on the tool. With the aged Rene 41 under the same cutting conditions and a wearland on the tool of .016", the tool life was 75 inches of work travel per tooth.

The face milling tests indicated that the non-ferrous grades of carbide, K-8 (C-3), 44A (C-1), and 883 (C-2), gave the best tool life, Figure 218, page 188. Tool life for these grades of carbide was 25 to 30 inches of work travel per tooth using a cutting speed of 63 feet/minute, a feed of .0065 in./tooth and a chlorinated oil cutting fluid. Tool life for the 370 (C-6) steel cutting grade of carbide was about ten inches of work travel per tooth under the same machining conditions.

A tool geometry evaluation in face milling the aged Rene 41 with K-8 (C-3) grade of carbide indicated that a cutter with an axial rake of 0°, a radial rake of 7° and a 45° corner angle gave the best tool life, Figure 219, page 189. Tool life with this geometry on the cutter was 30 inches of work travel per tooth.

The effect of cutting speed and cutting fluid in face milling aged Rene 41 with carbide tools is shown in Figure 220, page 189. Best tool life, 30 inches work travel per tooth, was obtained with a highly chlorinated oil cutting fluid at a cutting speed of 63 feet/minute and a feed of .0065 in./tooth. It was noted that chip welding was minimized by use of a highly chlorinated oil, as compared to cutting dry or using a soluble oil.

Figure 221, page 190, shows the effect of feed on tool life in face milling Rene 41 aged to 365 BHN. Maximum tool life was obtained at a feed of .007 in./tooth with a cutting speed of 63 feet/minute.

Climb milling provides the best tool life in face milling Rene 41 aged to 365 BHN, Figure 222, page 190. Tool life obtained in down milling was 30 inches work travel per tooth, compared to 12 inches for the workpiece and cutter centered, and about five inches for up or conventional milling.

Face Milling Tests (continued)

Figure 223, page 191, presents tool life curves for face milling Rene 41 in both the solution treated and the solution treated and aged conditions. A comparison of the tool life curves indicates that there was no appreciable difference in the face milling characteristics of these two heat treated conditions of Rene 41 with the carbide cutter.

Slotting Tests

The results of the slotting tests on Rene 41 solution treated to 321 BHN and Rene 41 solution treated and aged to 365 BHN are given in Figures 224 through 227, pages 191 through 193.

The effect of speed in slotting solution treated Rene 41 with K-6 (C-2) carbide tools is shown in Figure 224, page 191. The best tool life, 48 inches of work travel per tooth, was obtained at a cutting speed of 25 feet/minute, a feed of .003 in./tooth, with a highly chlorinated oil cutting fluid, and using a 0° radial rake. However, a 50% increase in cutting speed was obtained for the same tool life by using a radial rake of 5°.

The effect of feed in slotting solution treated Rene 41 with carbide cutters is shown in Figure 225, page 192. At a cutting speed of 94 feet/minute, best tool life was obtained using a feed of .003 in./tooth. Tool life decreased with increasing feeds between .003 and .007 in./tooth.

The effect of feed in slot milling aged Rene 41 with K-6 (C-2) grade carbide is shown in Figure 226, page 192. The best tool life, 33 inches of work travel per tooth, was obtained at a feed of .003 in./tooth. As the feed per tooth was increased, tool life decreased.

In slot milling aged Rene 41 with K-6 (C-2) carbide tools, Figure 227, page 193, the best tool life, 80 inches of work travel per tooth, was obtained at a cutting speed of 65 feet/minute, a feed of .003 in./tooth, with a highly chlorinated oil as a cutting fluid. As cutting speed was increased, the tool life decreased rapidly.

End Milling Tests

The results of the end milling tests made on Rene 41 aged to 365 BHN are shown in Figures 228 through 231, pages 193 through 195. End milling tests were made using the end mill as a slotting cutter, in which the cutting was done with the end of the tool. Also, end milling tests were performed using the side or periphery of the end mill.

Tool life curves obtained in end mill slotting aged Rene 41 at 365 BHN with different grades of high speed steel end mills are shown in Figure 228, page 193.

End Milling Tests (continued)

Type T-15 high speed steel provided much better tool life than the type M-2 high speed steel. The aged Rene 41 show a high sensitivity to cutting speed in end mill slotting. With a type T-15 high speed steel end mill, a sharp peak was noted in the tool life curve. Tool life decreased at cutting speeds higher and lower than 18 feet/minute. The sensitivity to change in cutting speed was not as great with the M-2 high speed steel cutter. However, it should be pointed out that the T-15 end mill showed chipping of the cutting edges during the testing. Normal wear was noted on the cutting edges of the M-2 high speed steel end mill.

Of the various cutting fluids tested in end mill slotting of aged Rene 41, soluble oil (1:20) gave the best tool life, Figure 229, page 194. Tool life was 13 inches of work travel with the soluble oil, compared to five inches for highly sulphurized oil and three inches with a highly chlorinated oil, at a cutting speed of 22 feet per minute.

Figure 230, page 194, shows the effect of feed for the T-15 and M-2 high speed steel end mills in end mill slotting of aged Rene 41. Best tool life was obtained at a feed of .002 in./tooth for the type T-15 high speed steel end mill, and at a feed of .003 in./tooth for the M-2 high speed steel end mill. Note that chipping occurred on the T-15 cutter even at the light feed of .002 in./tooth.

The end milling tests on aged Rene 41 in which the cut was made with the periphery of the cutter, Figure 231, page 195, show that the flute length affects tool life appreciably in end milling. With a 3/4" diameter cutter having a standard flute length of 2", cutter breakage occurred and no appreciable tool life could be obtained. By reducing the flute length of overhang of the end mill to 1", a tool life of about 50 inches of work travel was obtained at a cutting speed of 18 feet/minute and a feed of .002 in./tooth.

Drilling Tests

Heavy web and standard twist drills with split and notched points were used in drilling the Rene 41 alloy, see Figure 232, page 196. As shown in Figure 233, page 197, the drill life on the Rene 41 solution treated and aged was considerably higher for the heavy web drills. Note how rapidly drill life dropped as the drill speed was either increased or decreased from the optimum speed at 17 feet per minute. With the heavy web drill and the regular helix, 70 holes were drilled at 17 feet/minute and only nine holes at 25 feet/minute. At 13 feet/minute, the drill life was 30 holes.

Further tests with various cutting fluids indicated that active cutting oils should be used, see Figure 234, page 197. The highly chlorinated oil was the best. The feed is very critical. For example, in Figure 235, page 198, at a drill speed of 17 feet/minute the drill life was 70 holes at a feed of .002 in./rev.; 26 holes at a feed of .001 in./rev.; and only 18 holes at a feed of .005 in./rev.

Drilling Tests (continued)

The feed must also be selected carefully in drilling Rene 41 in the solution treated condition. As shown in Figure 236, page 198, drill life was appreciably greater at a feed of .002 in./rev. than at .001 in./rev.

The point angle is another important factor in the drilling of the Rene 41 alloy. Note in Figure 237, page 199, that the drill life increased from 60 holes to 90 holes when the drill point was changed from 135 to the double point angle of 118° and 90°. The improvement in drill life with the double point angles also resulted with the solution treated and aged heat treatments, see Figure 238, page 199. With the aged condition, the drill life was increased from 70 holes (see Figure 235, page 198) to 90 holes by changing the point angle to the 118° and 90° point angles.

Reaming Tests

In reaming Rene 41 solution treated, the feed should not exceed .005 in./rev. For as shown in Figure 239, page 200, the reamer life will drop more than 50% if the feed is increased from .005 to .009 in./rev. Also the cutting speed should be held very close to the optimum speed of 25 feet/minute. Changing the cutting speed to 20 feet/minute results in a 25% decrease in reamer life and increasing the speed to 30 feet/minute results in a 75% decrease in reamer life, see Figure 240, page 200.

The maximum feed to be used in reaming Rene 41 in the solution treated and aged condition is also .005 in./rev. as shown in Figure 241, page 201. The shape of the tool life curve in reaming in Figure 242, page 201, indicates that the critical reaming speed for the solution treated and aged Rene 41 is 20 feet/minute.

Tapping Tests

The proper selection of the type of tap must be made in order to tap a reasonable number of holes in solution treated Rene 41. For as shown in Figure 243, page 20 99 holes were tapped with a 2 flute spiral point tap, while less than 20 holes were tapped with a 3 or 4 flute tap.

Large differences in tap life were also found with the various types of cutting fluid, see Figure 244, page 203. As the cutting fluid was changed from a soluble oil to a highly sulphurized oil to a highly chlorinated oil, the tap life doubled each time.

While the tap life with a 2 flute spiral point tap is reasonably good, the cutting speed must be kept low. Note in Figure 245, page 203, that at 13 feet/minute 99 holes were tapped and at 16 feet/minute, the tap life was only 50 holes.

Tapping Tests (continued)

The conditions for tapping Rene 41 in the solution treated and aged condition are even more critical than those for the solution treated condition, see Figure 246, 247 and 248, pages 204 and 205. The best tap life with the 2 flute spiral point tap was seven times that obtained with the second best 3 flute tap. The highly chlorinated oil was four times better than the highly sulphurized oil, and increasing the cutting speed from 5 feet/minute to 7 feet/minute resulted in a 60% decrease in tap life.

Surface Grinding Tests

The results of the surface grinding tests on solution treated and aged Rene 41 at 365 BHN are given in Figures 249 through 255, pages 205 through 208.

Figure 249, page 205, shows the grinding ratio obtained with three different grades of wheels. Although the 32A46L5VBE wheel gave the best G ratio, severe chatter marks were noted on the surface of the test specimen. Both the 32A46H8VBE and 32A46J8VBE wheels produced good surface finishes of about 15 to 20 microinches.

The effect of grinding wheel speed when grinding aged Rene 41 using a 32A46J8VBE wheel is shown in Figure 250, page 206. The best grinding ratio was obtained at a wheel speed of 6000 feet/minute. As wheel speed was reduced, the grinding ratio was reduced.

G ratio increased with decreasing down feed when surface grinding aged Rene 41, Figure 251, page 206. With the 32A46J8VBE wheel, the grinding ratio increased as the down feed was reduced for both the 6000 feet/minute wheel speed and the 4000 feet/minute wheel speed.

The effect of cross feed in surface grinding aged Rene 41 is given in Figure 252, page 207. At the 6000 feet/minute wheel speed, the grinding ratio increased as the cross feed was decreased. At the 4000 feet/minute wheel speed, a change in cross feed did not appreciably affect the grinding ratio.

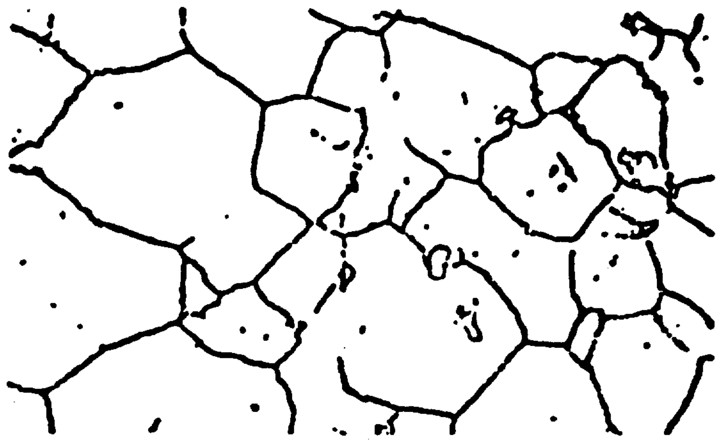
The effect of table speed on the grinding ratio obtained in grinding Rene 41 aged to 365 BHN is more noticeable at the 6000 feet/minute wheel speed than at 4000 feet/minute, Figure 253, page 207. A very distinct increase in G ratio was noted at the 6000 feet/minute wheel speed when the table speed was decreased from 40 feet/minute to 20 feet/minute.

Figure 254, page 208, shows the effect of grinding fluid in surface grinding of aged Rene 41. G ratios increased with increased wheel speed for both the highly sulphurized and the highly chlorinated oils. With the soluble oil grinding fluid, the grinding ratio remained about the same for all wheel speeds.

Surface Grinding Tests (continued)

The effect of wheel grade, structure and grain size is shown in Figure 255, page 208. A much better G ratio was obtained with the finer grit wheel, 32A80J5VBE, than with any of the 46 grit wheels tested. Using a grinding wheel with a more open structure, such as 12 as compared to 8, appears to improve the grinding ratio slightly when using 46 grit wheels.

Microstructures of Rene 41



Solution Treated Condition, 321 BHN
Microstructure shows equiaxed grains plus free and grain-boundary carbides.

Magnification: 1000X Etchant: Kalling's

Solution Treated and Aged, 365 BHN
Microstructure shows coalescence of grain-boundary carbides plus precipitation.

Magnification: 1000X Etchant: Kalling's

Figure 210

See Text, page 172

TABLE 14

RECOMMENDED CUTTING CONDITIONS FOR MACHINING RENE 41 SOLUTION TREATED TO 321 BHN

Nominal Chemical Composition, Percent

Cr	Co	Mo	Fe	Ti	C	Al	Ni
19.0	11.0	10.0	5.0	3.0	.10	1.5	Bal.

Operation	Tool Material	Tool Geometry	Tool Used for Tests	Depth of Cut inches	Width of Cut inches	Feed	Cutting Speed ft./min	Tool Life	Wear-land inches	Cutting Fluid
Turning	C-2 Carbide	BR: 0° SCEA: 15° SR: 5° ECEA: 15° Relief: 5° NR: 1/32"	1/2" square throwaway holder with mech. chip breaker	.062	-	.009 in/rev	70	40 min.	.016	Soluble Oil (1:20)
Turning	T-15 HSS	BR: 0° SCEA: 0° SR: 15° ECEA: 5° Relief: 5° NR: 1/32"	5/3" square tool bit	.062	-	.009 in/rev	12	75 min.	.010	Soluble Oil (1:20)
Face Milling	C-2 Carbide	AR: 0° TR: 5° RR: 7° Incl: -5° CA: 45° ECEA: 5° Clearance: 10°	4" diameter face mill	.060	2	.0065 in/tooth	50	28 in/tooth work travel	.030	Highly Chlorinated Oil
Face Milling	T-15 HSS	AR: 0° TR: 14° RR: 20° Incl: -14° CA: 45° ECEA: 5° Clearance: 10°	4" diameter face mill	.060	2	.011 in/tooth	22	80 in/tooth work travel	.012	Highly Chlorinated Oil
End Mill Slotting	M-2 HSS	30° RH Helix RR: 10° CA: 45° Peripheral Cl: 10° ECEA: 3°	3/4" diameter 4 tooth end mill 1" flute length	.250	3/4	.002 in/tooth	22	100 inches work travel	.020	Soluble Oil (1:20)
Slot Milling Down Milling	C-2 Carbide	AR: -5° bi-negative RR: 5° ECEA: 1° CA: 45° x .030" Clearance: 10°	6" diameter inserted tooth cutter	.125	1	.003 in/tooth	94	48 in/tooth work travel	.030	Highly Chlorinated Oil

TABLE 14 (continued)
RECOMMENDED CUTTING CONDITIONS FOR MACHINING
RENE 41 SOLUTION TREATED TO 321 BHN

Operation	Tool Material	Tool Geometry	Tool Used for Tests	Depth of Cut inches	Width of Cut inches	Feed	Cutting Speed ft./min.	Tool Life	Wear-land inches	Cutting Fluid
Drilling	T-15 HSS	118°/90° point angle, 3° clearance 29° helix angle split point	1/4" dia. heavy web type drill 2-1/2" O. L. 1-1/2" flute length	1/2" thru hole	-	.002 in/rev	17	90 holes	.020	Highly Chlorinated Oil
Tapping	M-10 HSS	2 flute plug tap spiral point 75% thread	5/16-24 NF plug tap	1/2" thru hole	-	-	12	98 holes	Tap break-age	Highly Chlorinated Oil
Reaming	M-2 HSS	6 flute straight chucking reamer CA: 45° Clearance: 10°	.272" diameter reamer	1/2" thru hole	-	.005 in/rev.	25	95 holes	.016	Highly Chlorinated Oil

See Text, page 172

TABLE 15
RECOMMENDED CUTTING CONDITIONS FOR MACHINING
RENE 41 SOLUTION TREATED AND AGED TO 365 BHN

Nominal Chemical Composition, Percent

Cr	Co	Mo	Fe	Ti	C	Al	Ni
19.0	11.0	10.0	5.0	3.0	.10	1.5	Bal.

Operation	Tool Material	Tool Geometry	Tool Used for Tests	Depth of Cut inches	Width of Cut inches	Feed	Cutting Speed ft./min	Tool	Wear-land inches	Cutting Fluid
Turning	C-2 Carbide	BR: 0° ECEA: 15° SR: 5° Relief: 5° SCEA: 15° NR: 1/32"	1/2" square throwaway holder with mech. chip breaker	.062	-	.009 in/rev	70	28 min.	.016	Soluble Oil (1:20)
Turning	T-15 HSS	BR: 0° ECEA: 5° SR: 15° Relief: 5° SCEA: 0° NR: 1/32"	5/8" square tool bit	.062	-	.009 in/rev	12	81 min.	.030	Highly Chlorinated Oil
Face Milling	C-2 Carbide	AR: 0° TR: 5° RR: 7° Incl: -5° CA: 45° ECEA: 5° Clearance: 10°	4" diameter face mill	.060	2	.0065 in/tooth	63	29 in/tooth work travel	.030	Highly Chlorinated Oil
Face Milling	T-15 HSS	AR: 0° TR: 22° RR: 30° Incl: -22° CA: 45° ECEA: 5° Clearance: 10°	4" diameter face mill	.060	2	.011 in/tooth	22	75 in/tooth work travel	.030	Highly Chlorinated Oil
End Mill Slotting	T-15 HSS	30° RH Helix RR: 10° CA: 45° Peripheral Cl: 10° ECEA: 3°	3/4" diameter 4 tooth end mill 1" flute length	.250	3/4	.002 in/tooth	18	69 inches work travel	.020	Soluble Oil (1:20)
Slot Milling Down Milling	C-2 Carbide	AR: -5° bi-negative RR: 5° ECEA: 1° CA: 45° x .030" Clearance: 10°	6" diameter single tooth inserted tooth cutter	.125	1	.003 in/tooth	61	80 in/tooth work travel	.016	Highly Chlorinated Oil

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TABLE 15

RECOMMENDED CUTTING CONDITIONS FOR MACHINING
RENE 41 SOLUTION TREATED AND AGED TO 365 BHN

Operation	Tool Material	Tool Geometry	Tool Used for Tests	Depth of Cut	Width of Cut	Feed	Cutting Speed ft./min	Tool Life	Wear-land inches	Cutting Fluid
Tapping	M-10 HSS	2 flute plug tap spiral point 75% thread	5/16-24 NF plug tap	1/2" thru hole	-	-	5	140 holes	Tap Breakage	Highly Chlorinated Oil
Reaming	M-2 HSS	6 flute straight chucking reamer CA: 45° Clearance: 10°	.272" diameter reamer	1/2" thru hole	-	.005 in/rev	20	96 holes	.016	Highly Chlorinated Oil
Drilling	T-15 HSS	118°/90° point angle, 3° clearance 29° helix angle split point	1/4" dia., heavy web type drill 2-1/2" O.L. 1-1/2" flute length	1/2" thru hole	-	.002 in/rev	17	95 holes	.020	Highly Chlorinated Oil

SURFACE GRINDING

Wheel Grade	Grinding Fluid	Wheel Speed feet/minute	Table Speed feet/minute	Down Feed inches/pass	Cross Feed inches/pass	G Ratio
32A46J8VBE	Highly Sulphurized Oil	4000	40	.001	.050	10

See Text, page 172

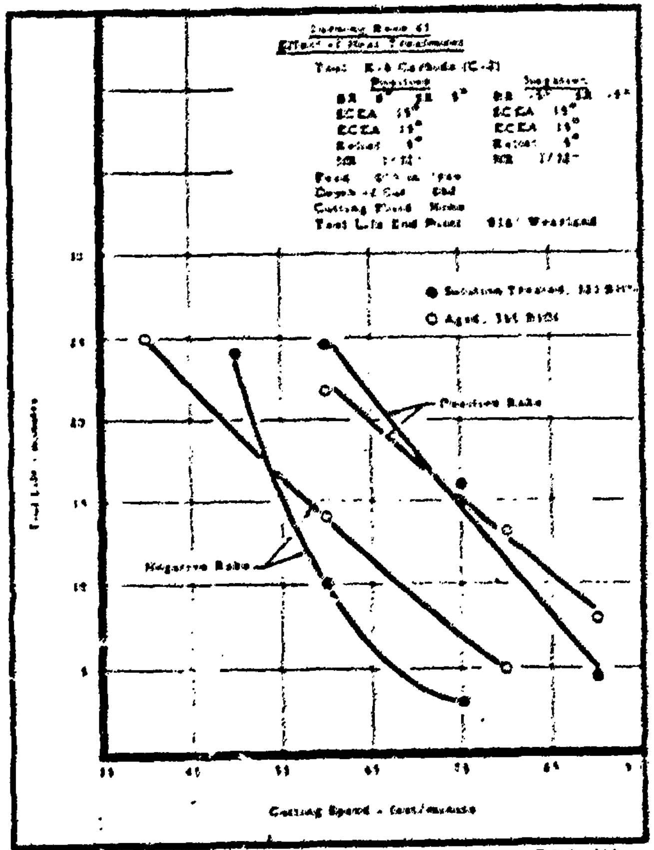

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Figure 21[illegible]

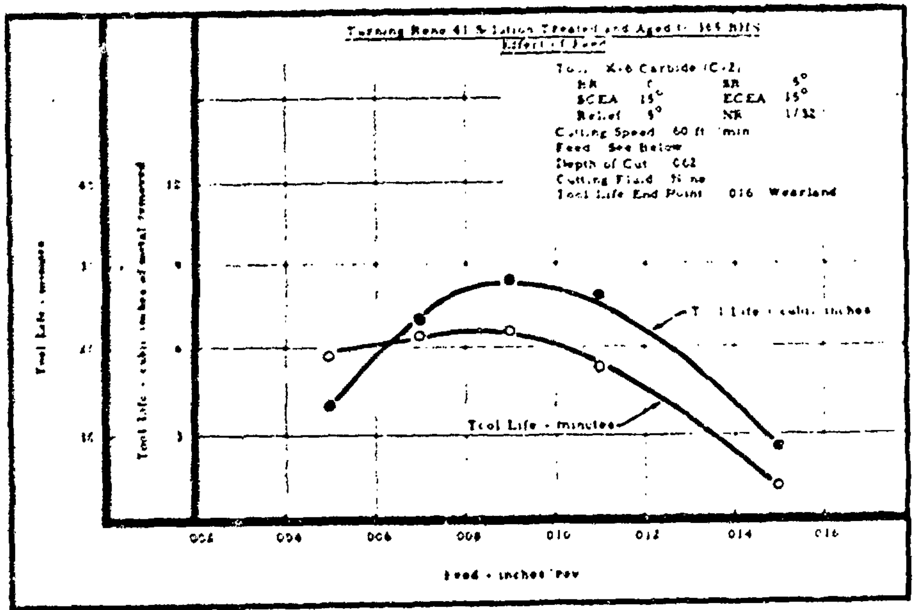

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Figure 21[illegible]

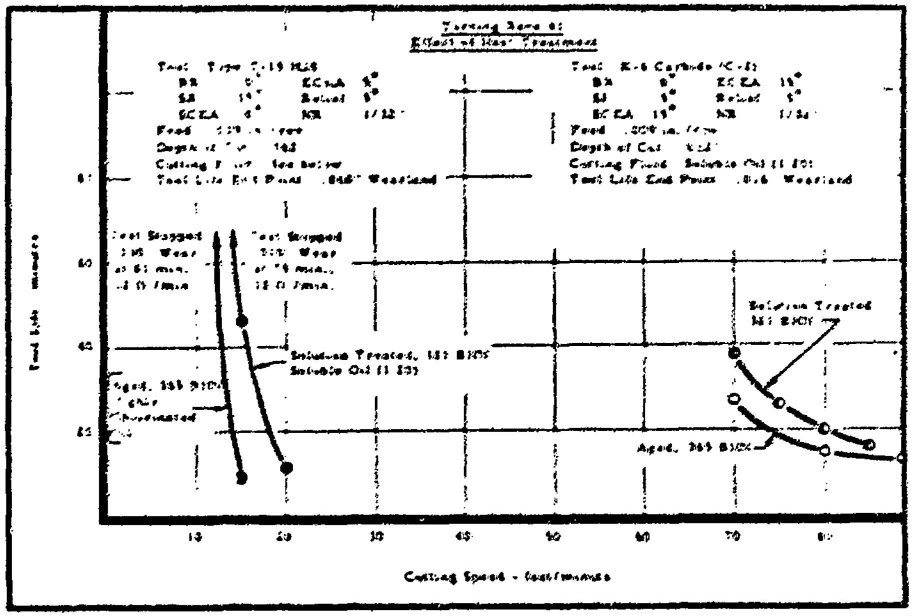

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Figure 213

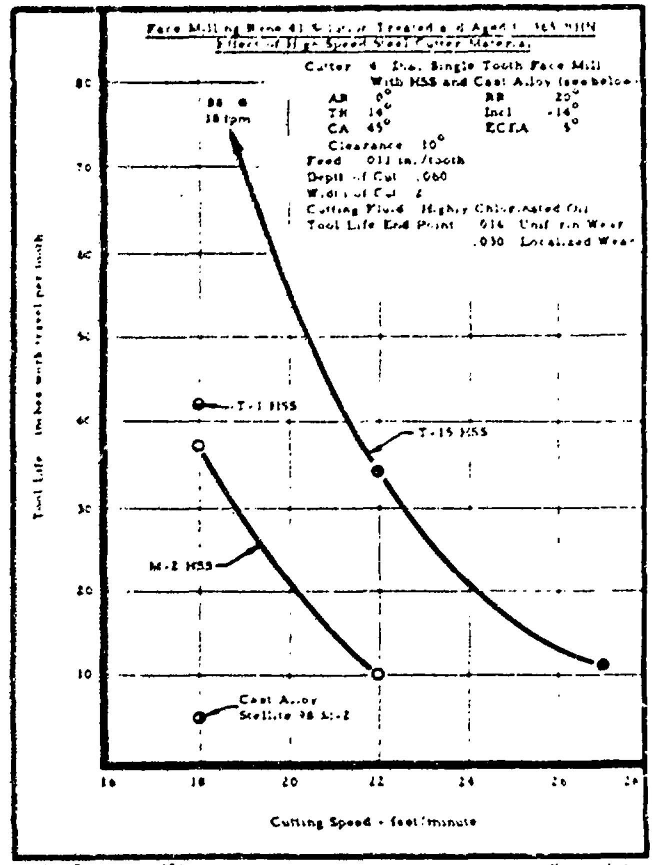

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Figure 214

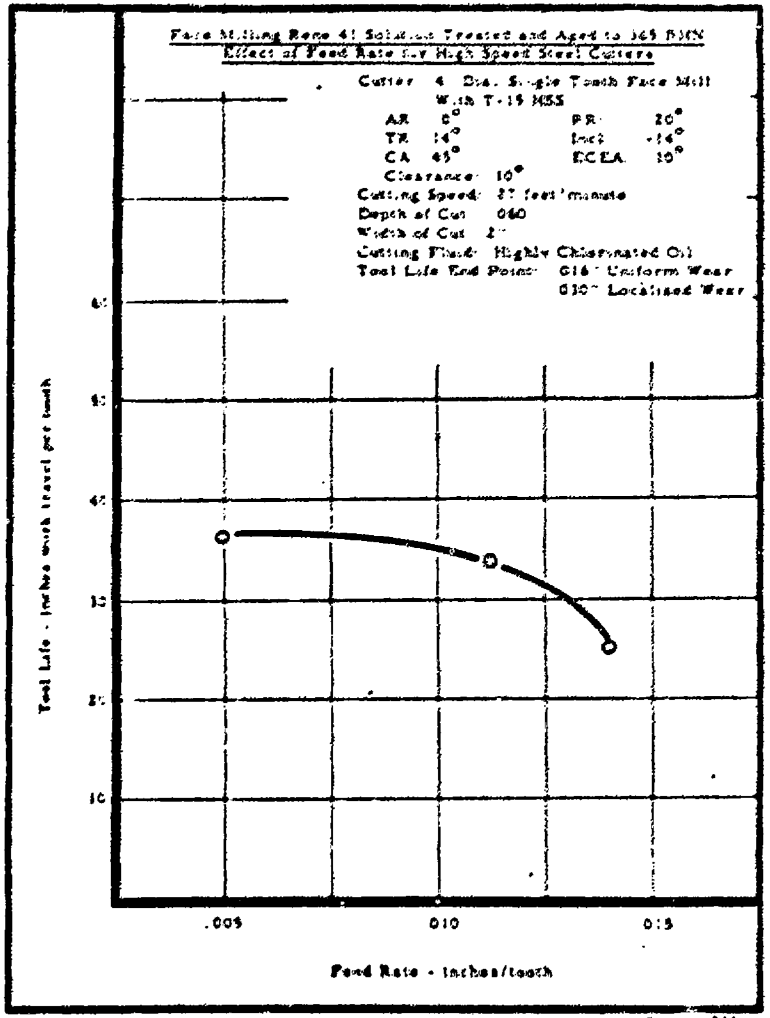

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Figure 215

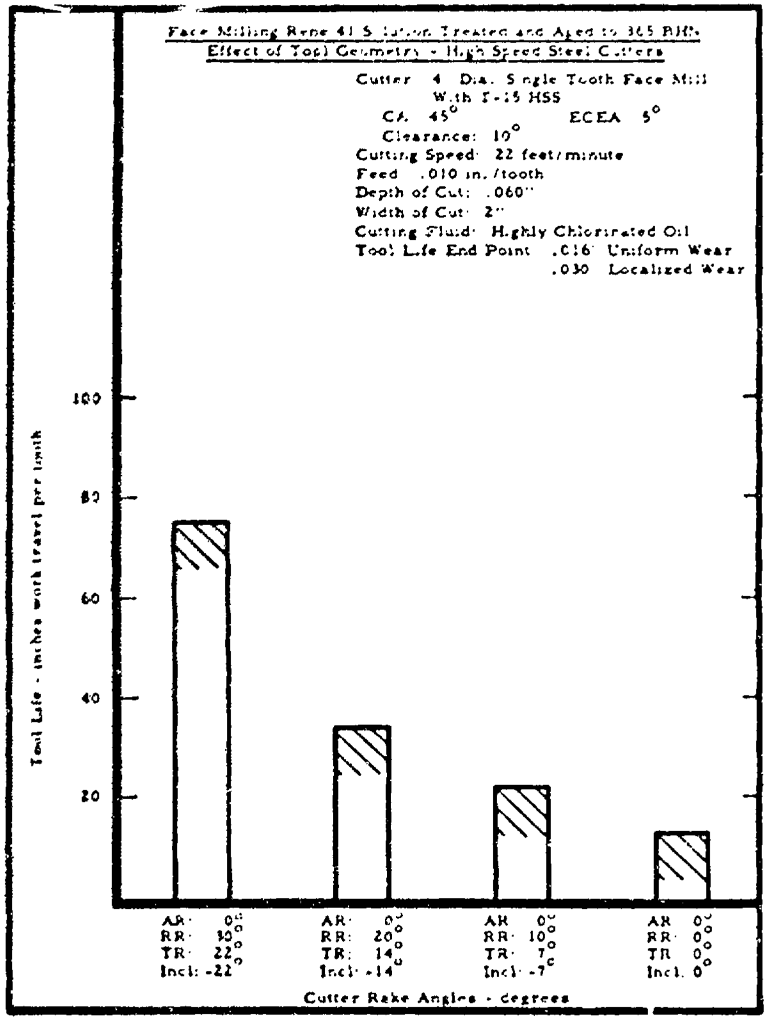

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Figure 216

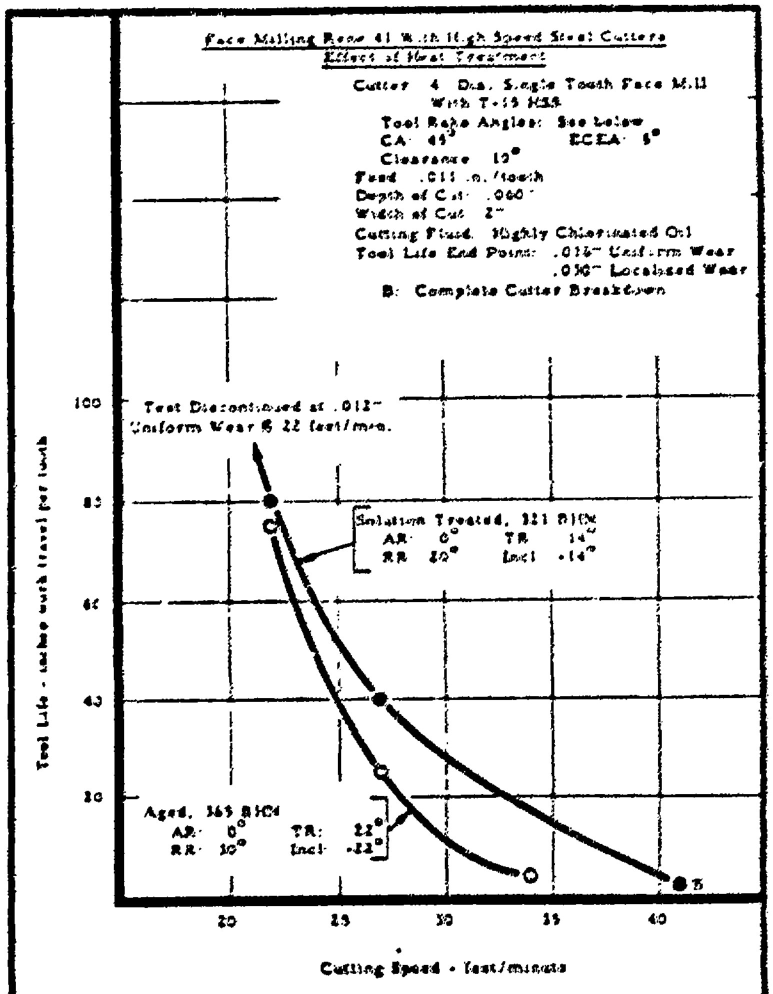

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Figure 217

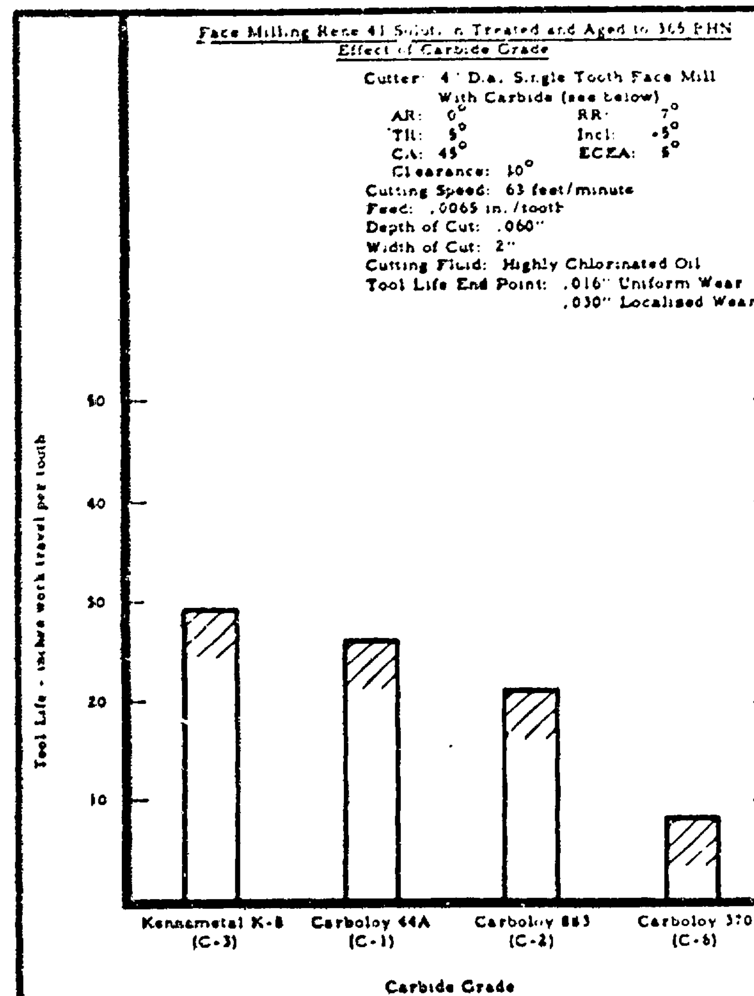

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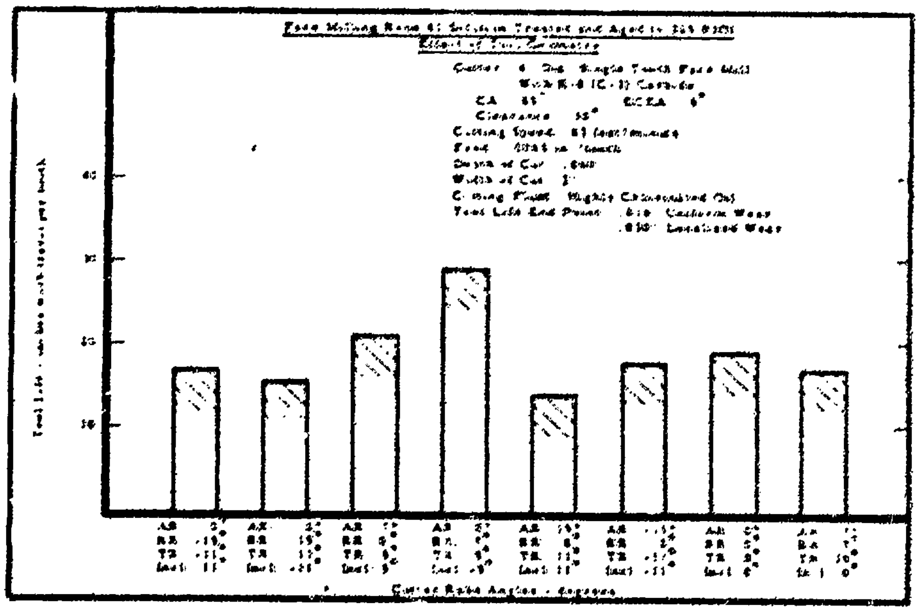
Figure 218



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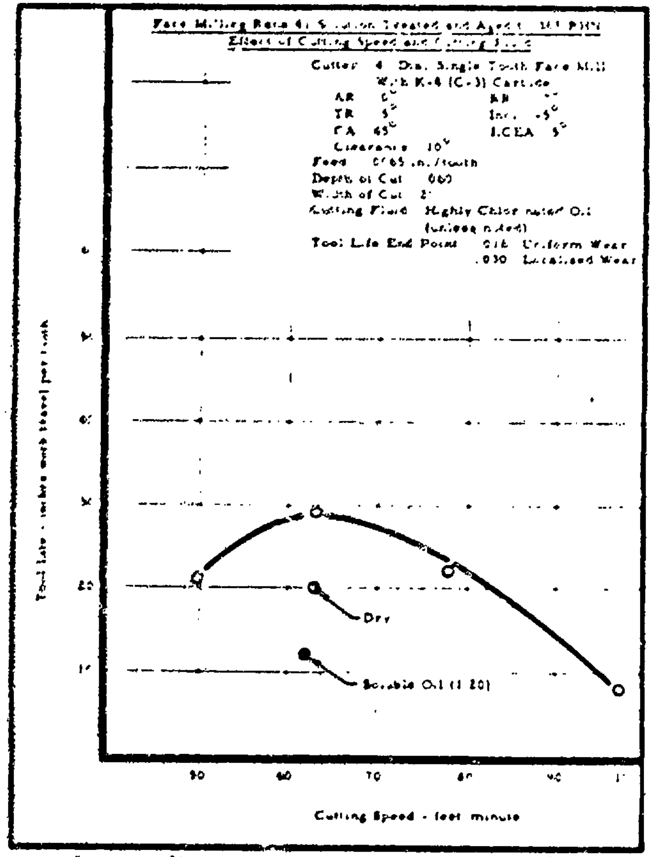

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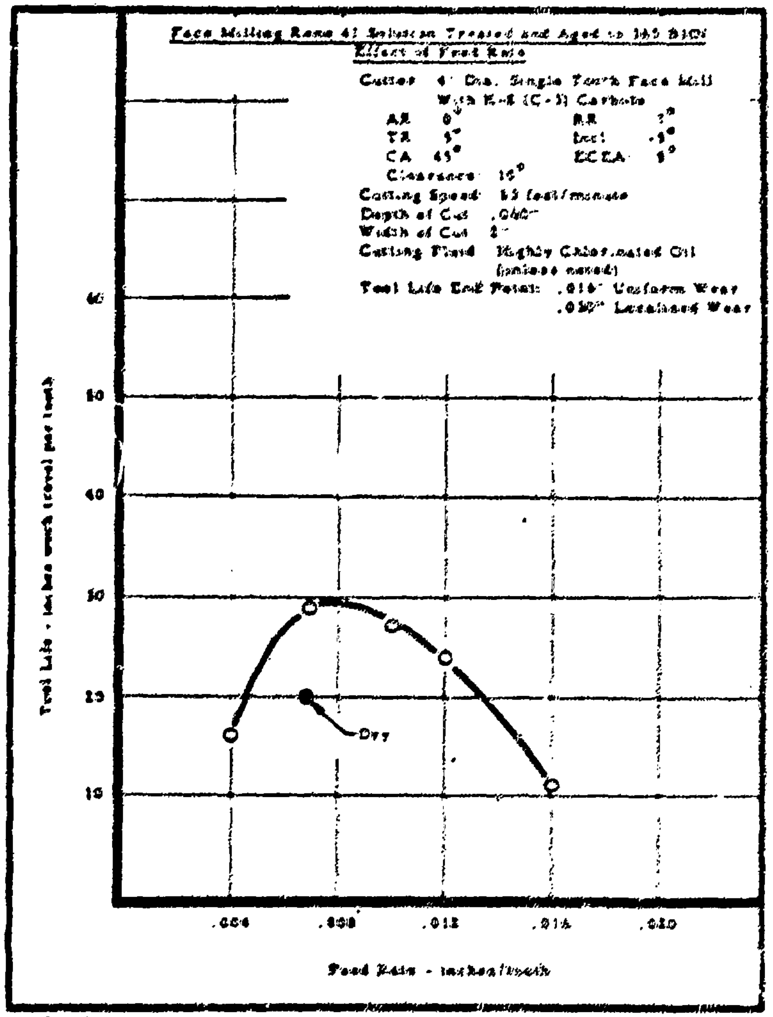

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Figure 221

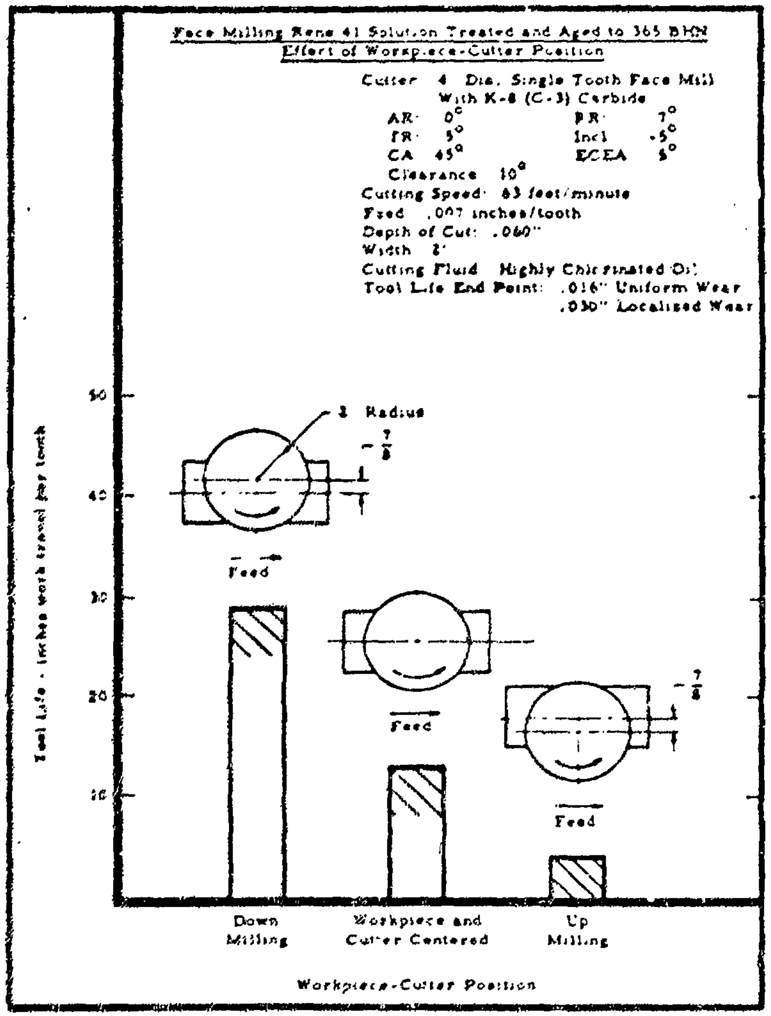

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Figure 222

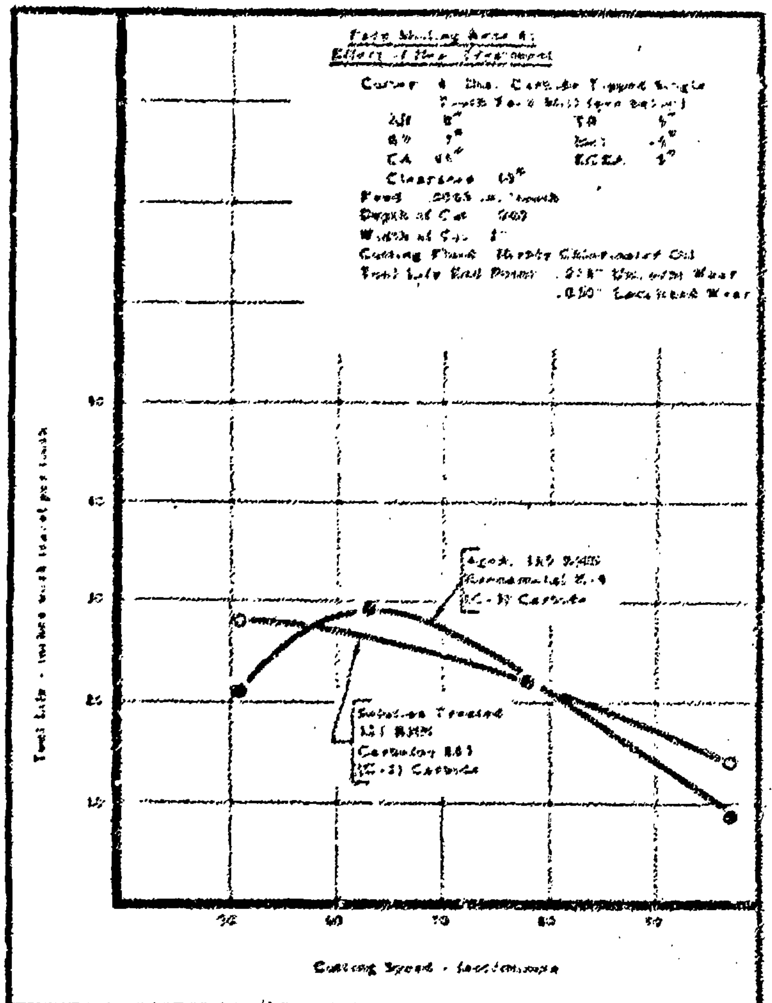

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Figure 225

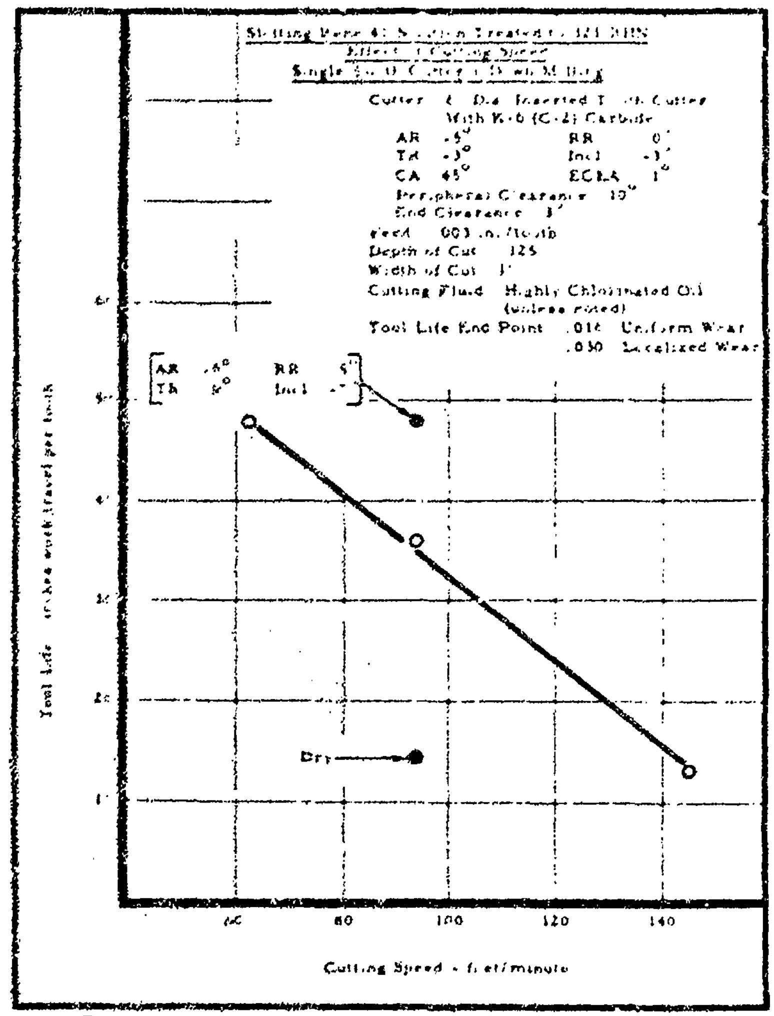

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Figure 224

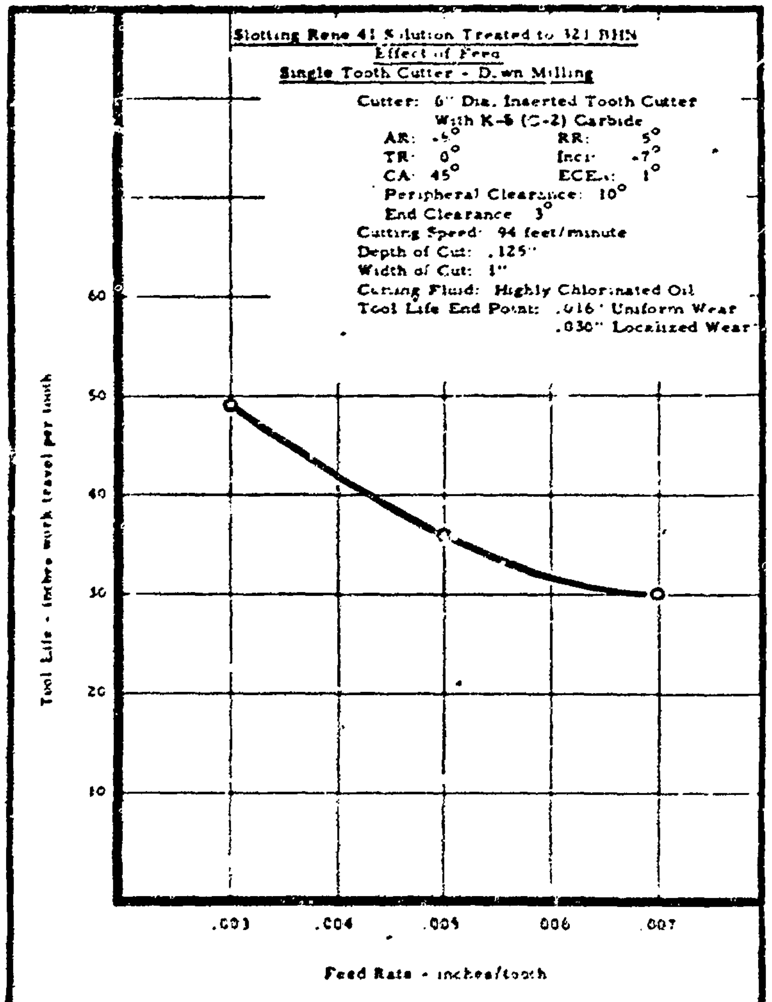

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Figure 225

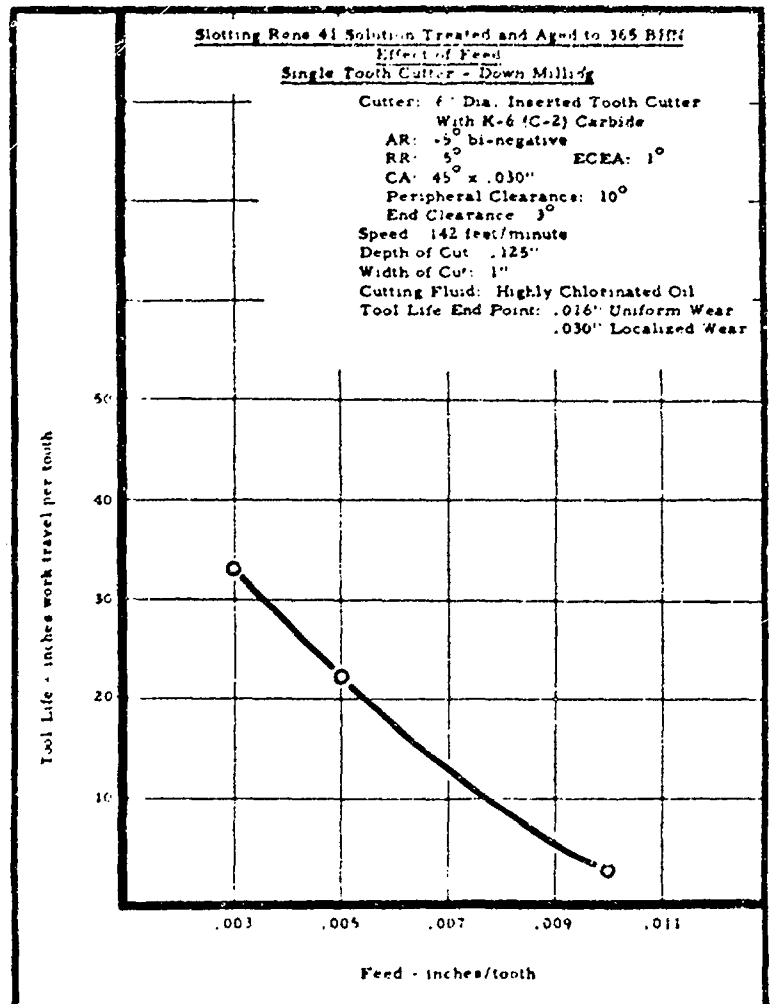

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Figure 226

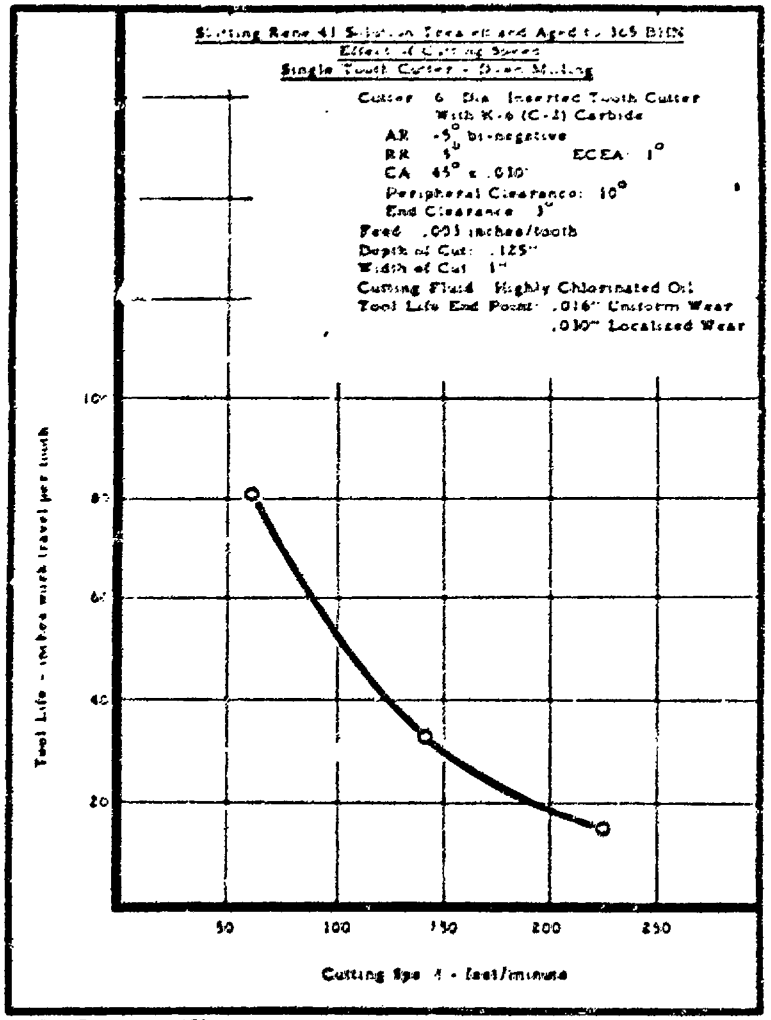

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Figure 227

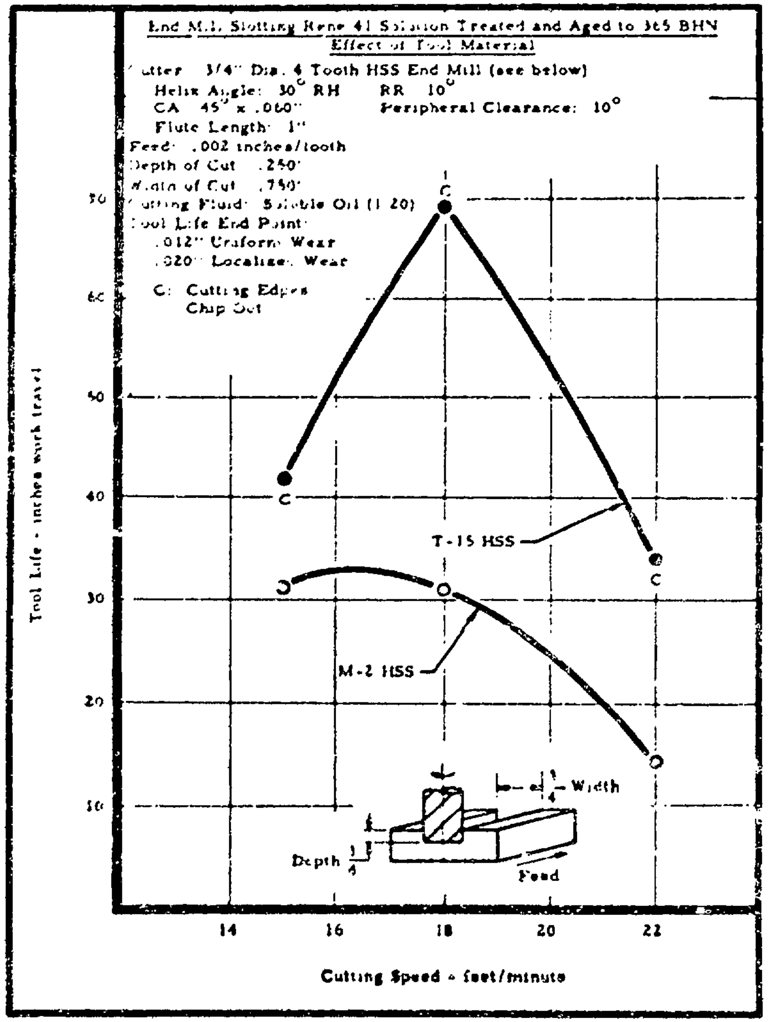

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Figure 228

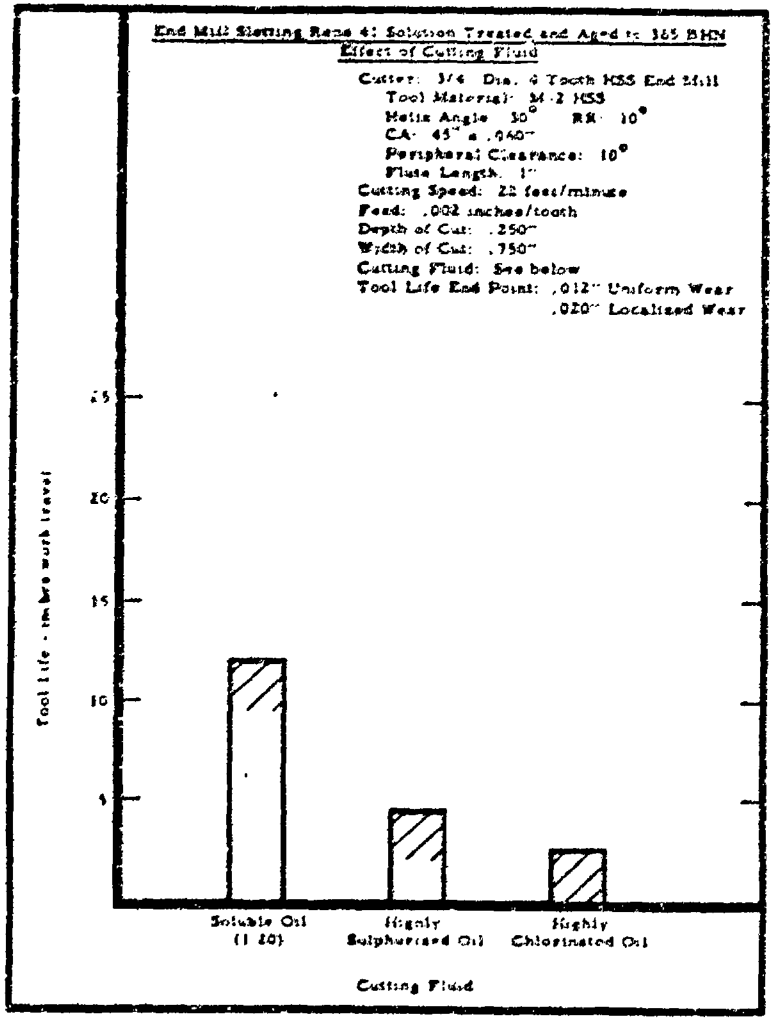

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Figure 229

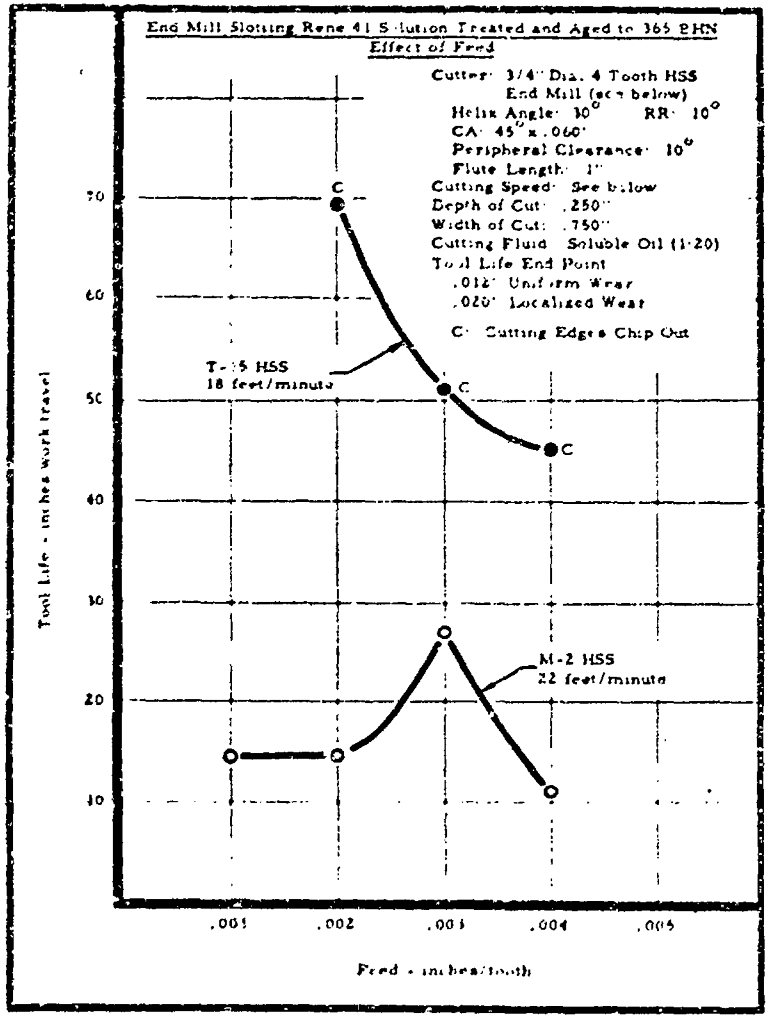

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Figure 230

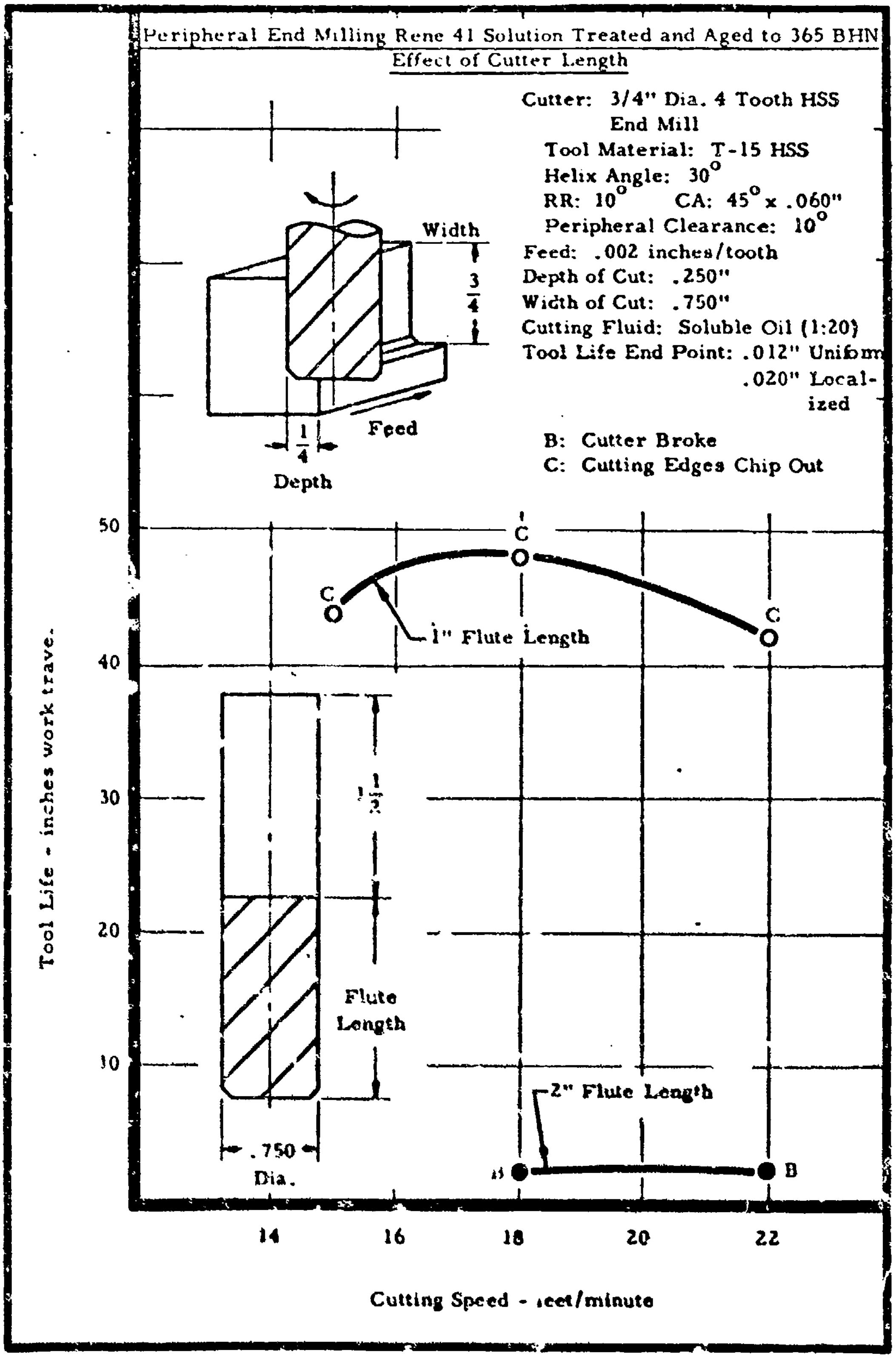

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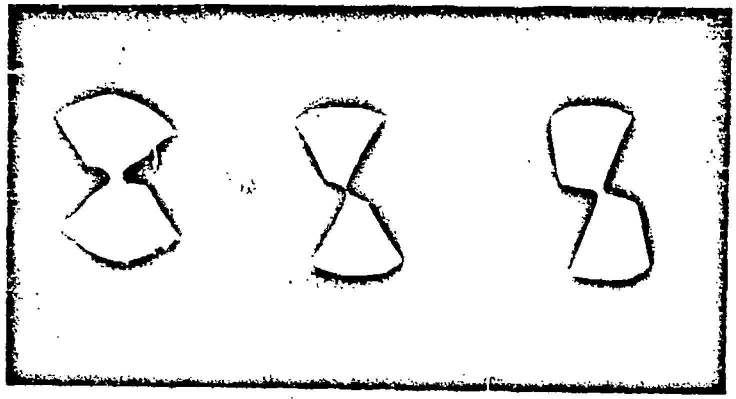
Figure 231



The three drill points shown above illustrate the difference in drill construction. The drill on the left is a heavy web drill with a split point. The drill in the center is a standard twist drill with a split point. Note the difference in web thickness between these two drills. The drill on the right shows a short flute heavy web drill with a notched point.

Figure 232

See Text, page 176

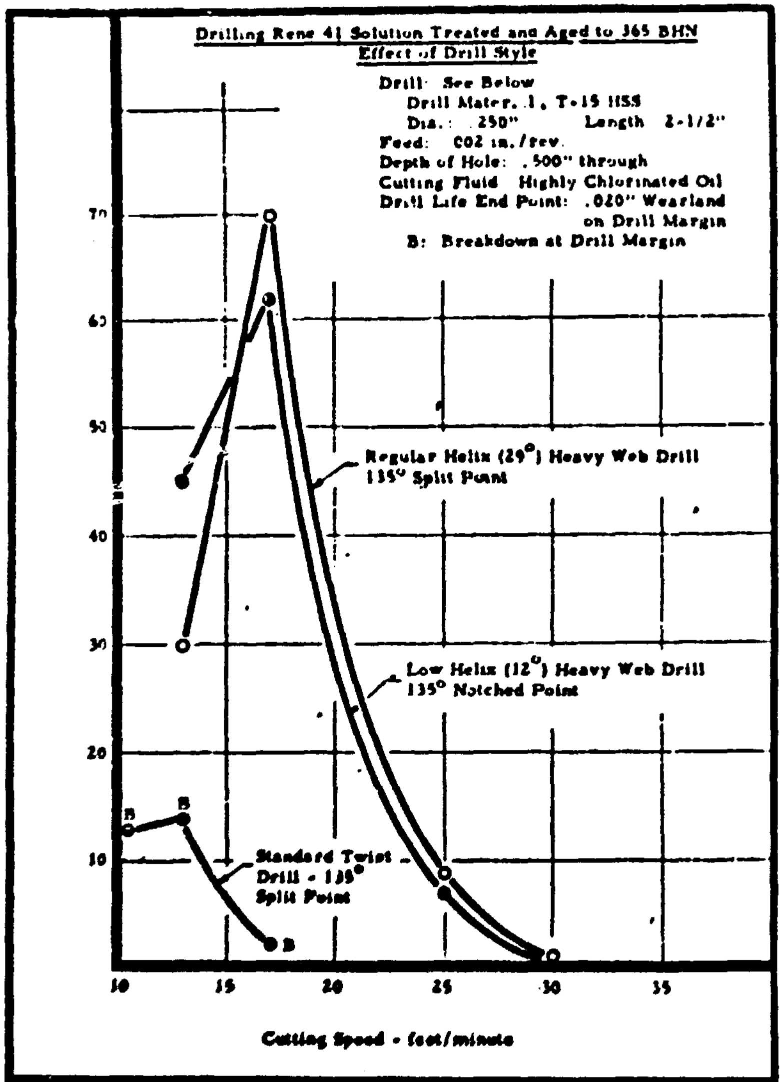


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Figure 233

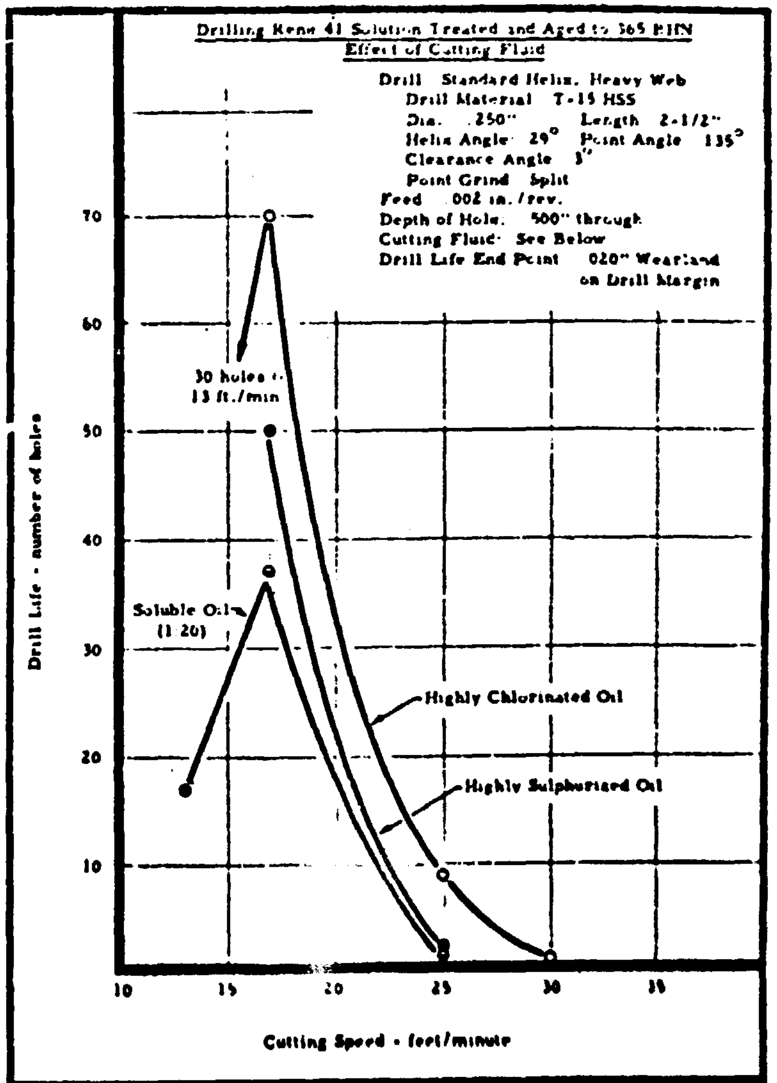

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Figure 234

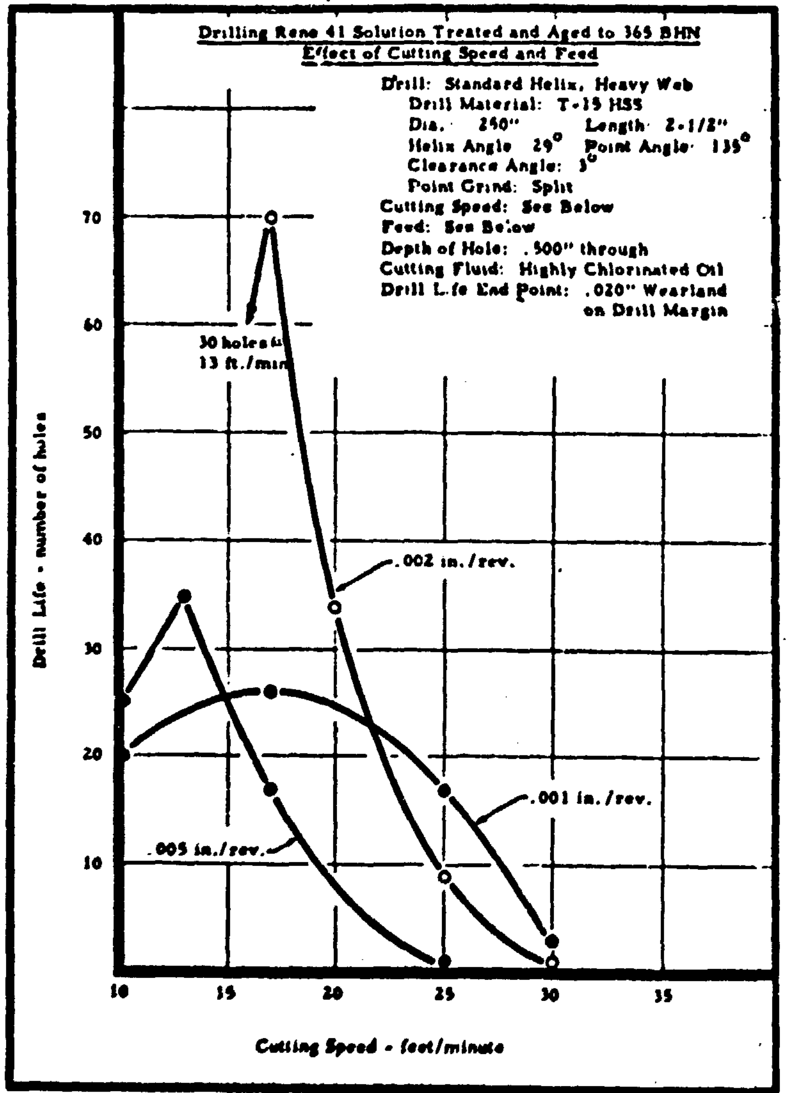

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Figure 215

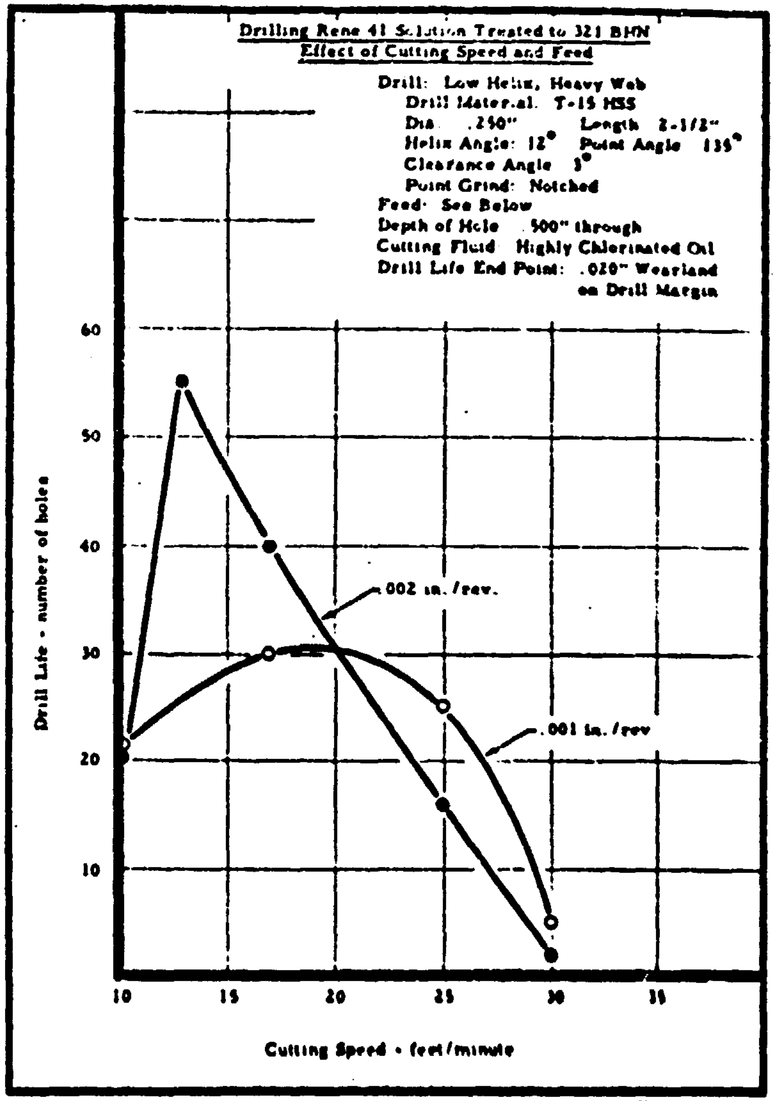

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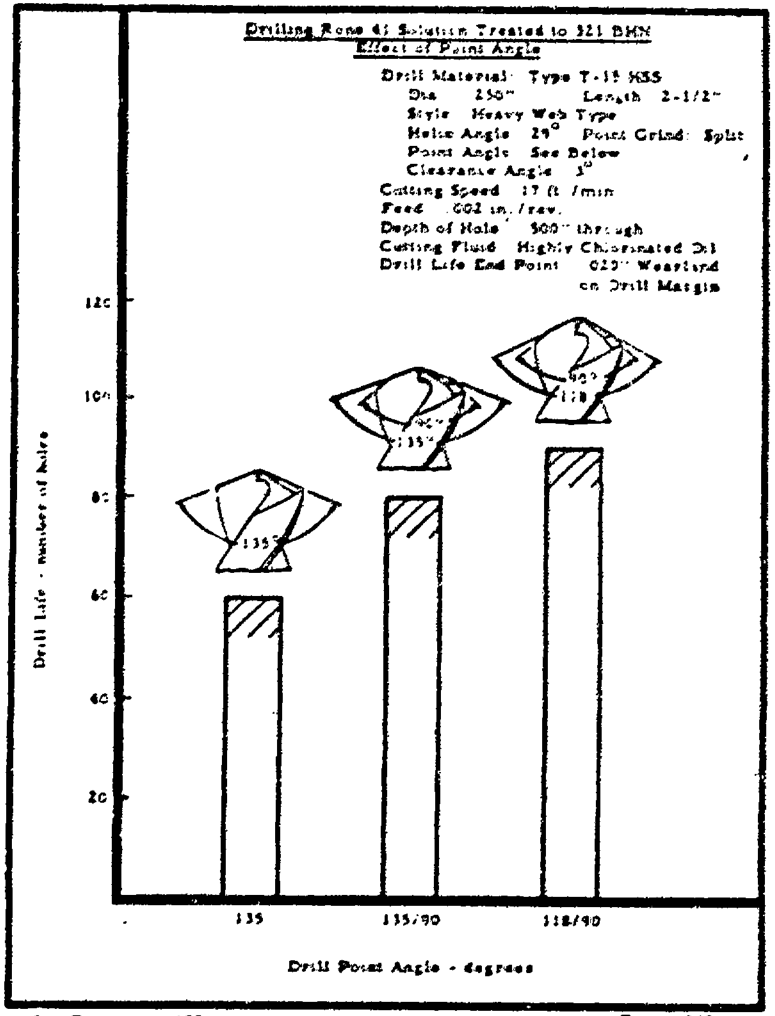
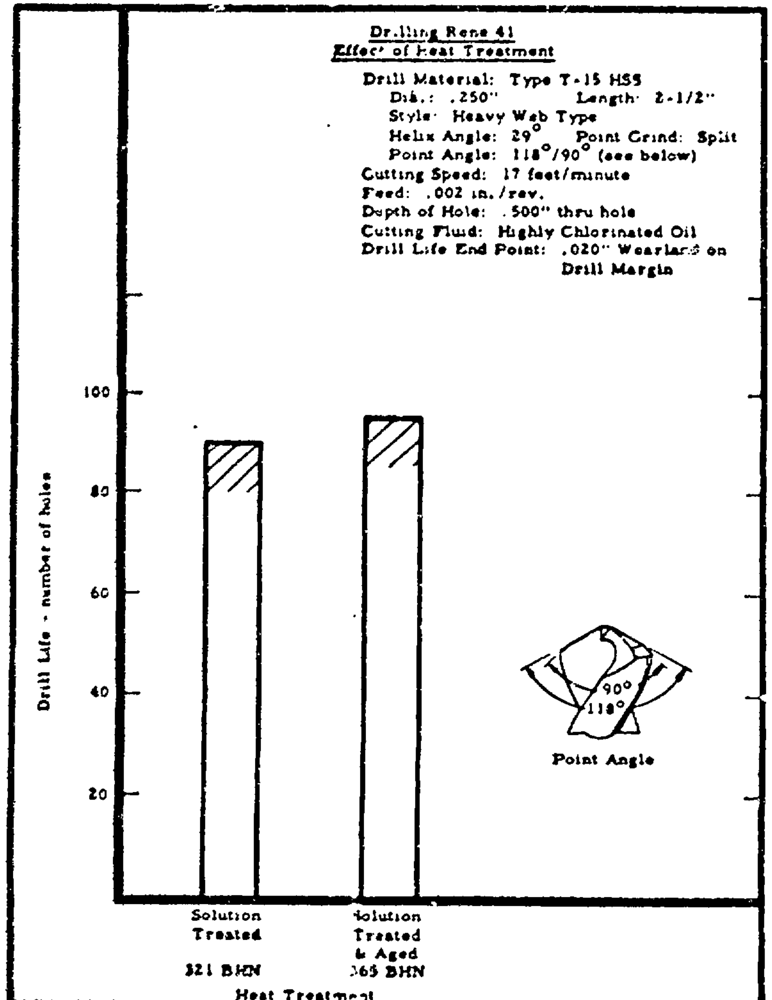
Figure 216



See Text, page 177 Figure 237



See Text, page 177 Figure 238

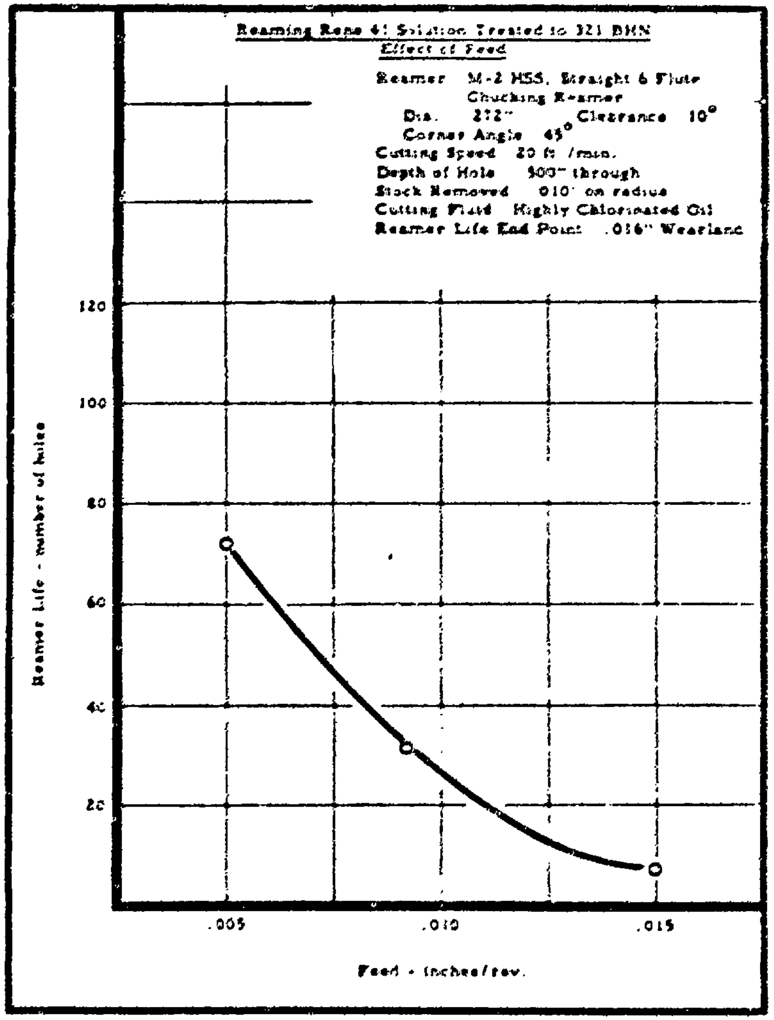


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Figure 239

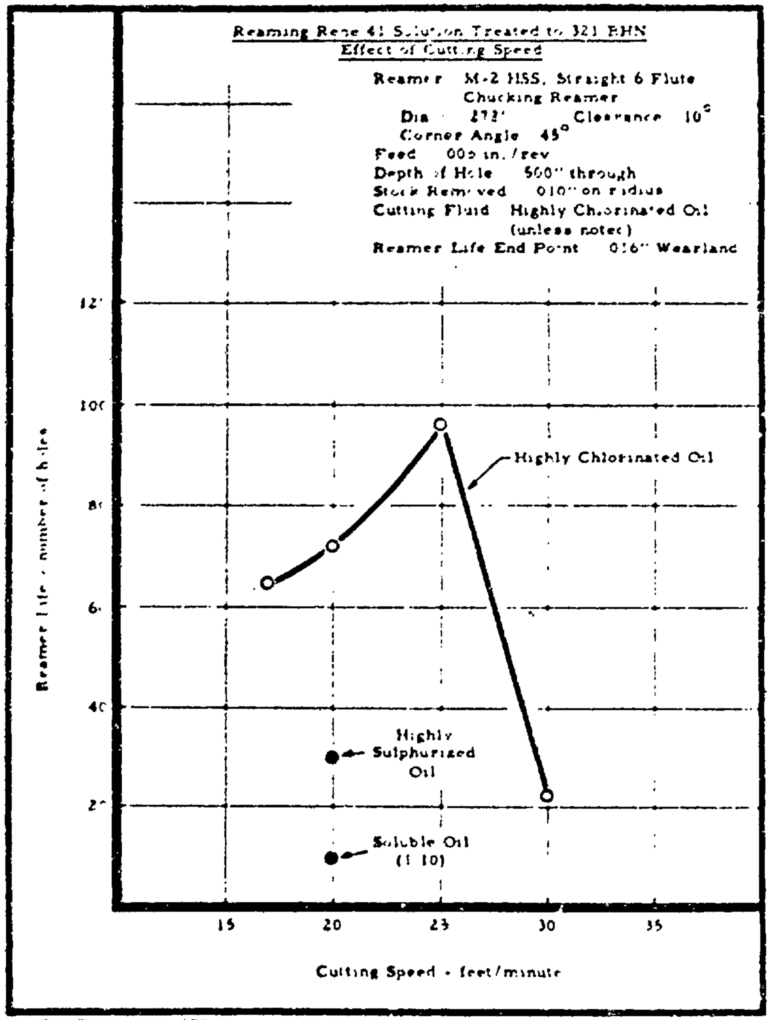

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Figure 240

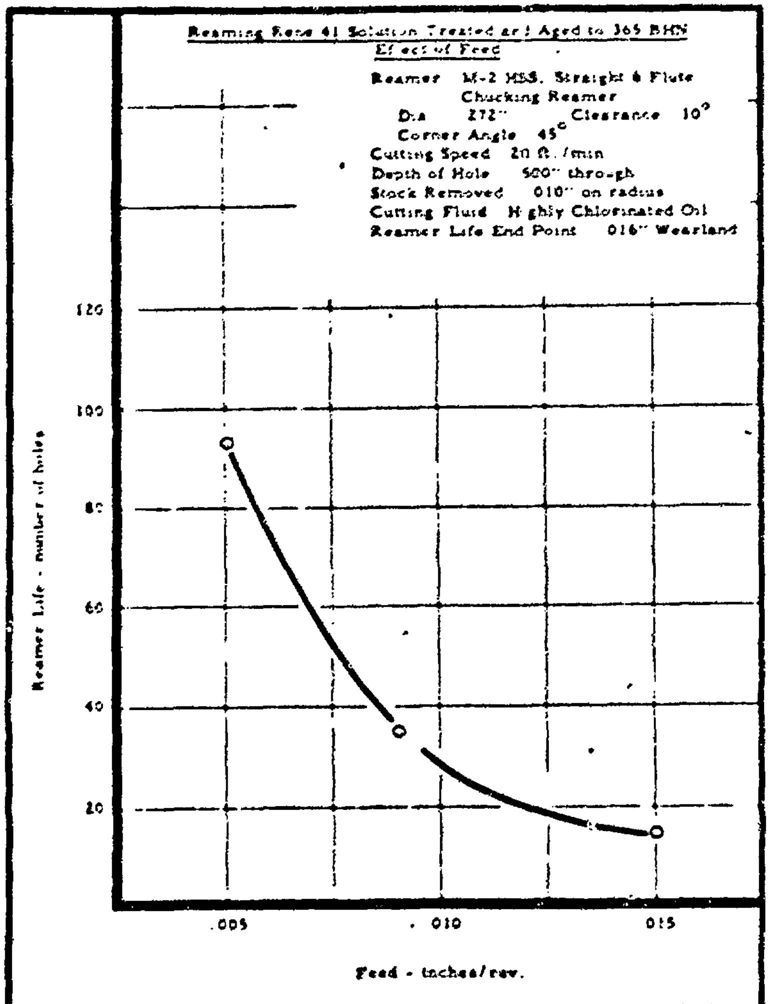

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Figure 241

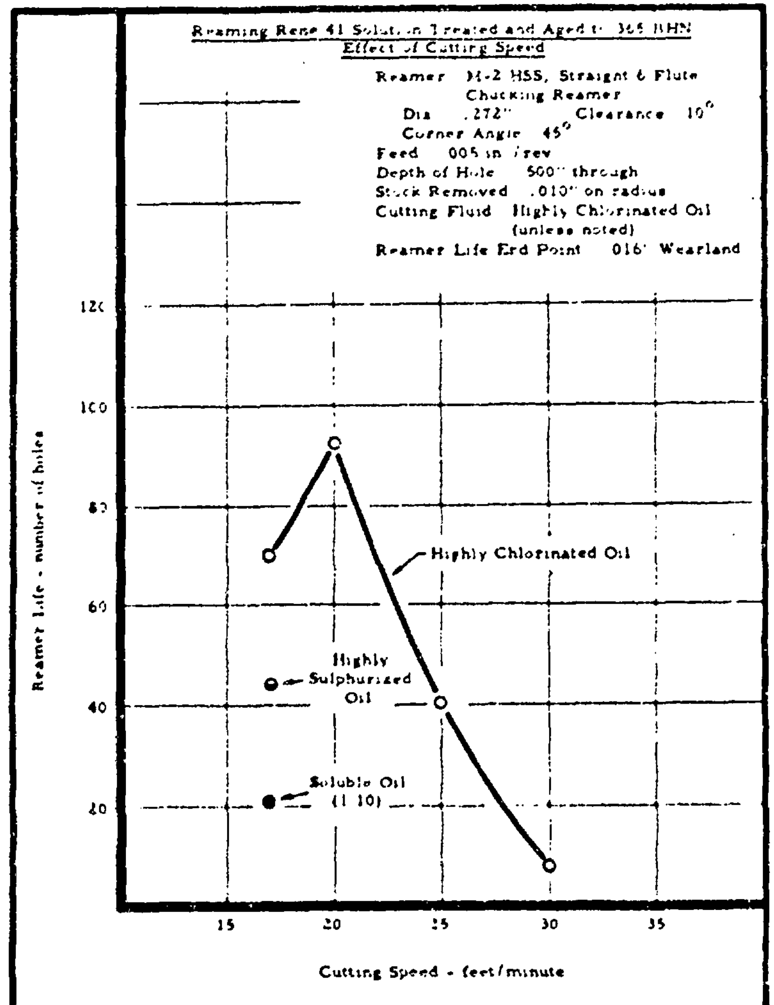

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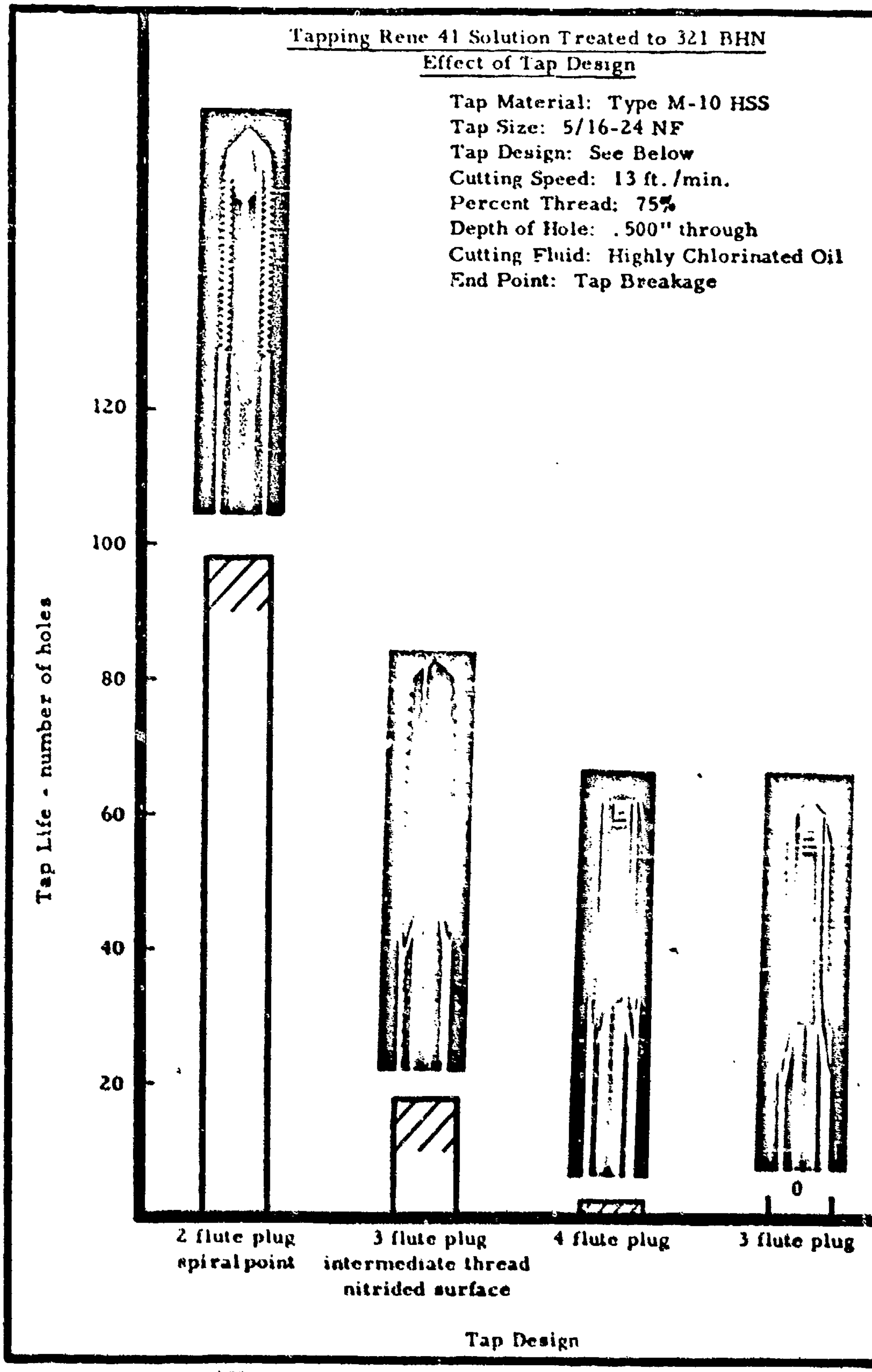
Figure 242



See Text, page 177

Figure 243

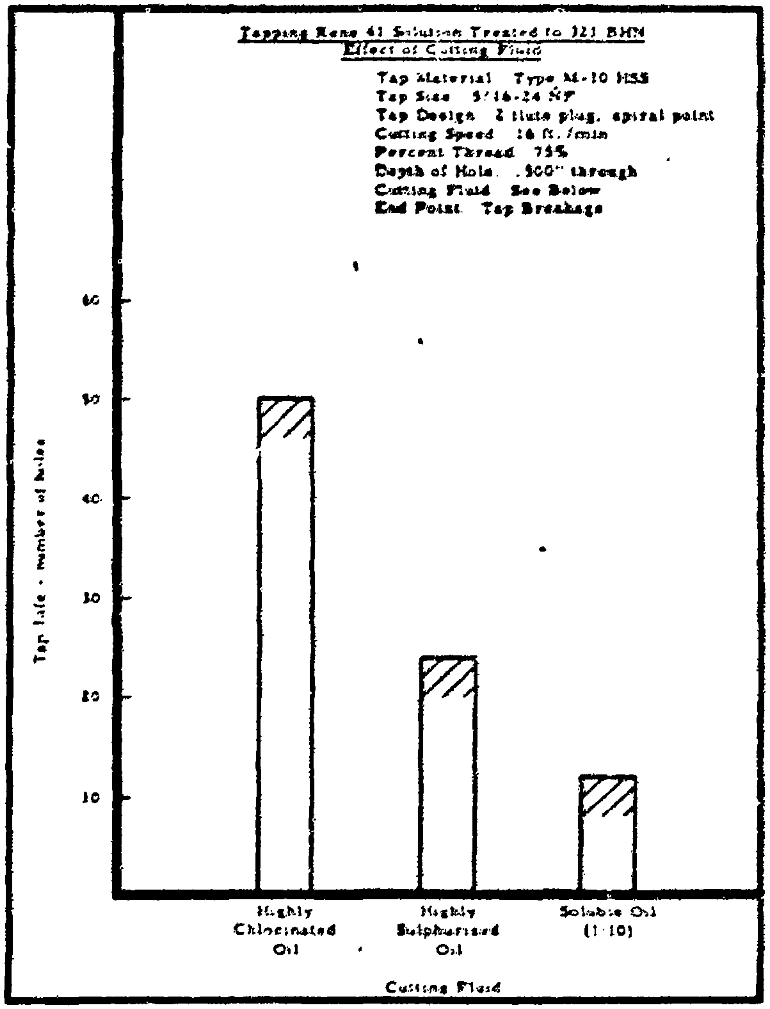


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Figure 244

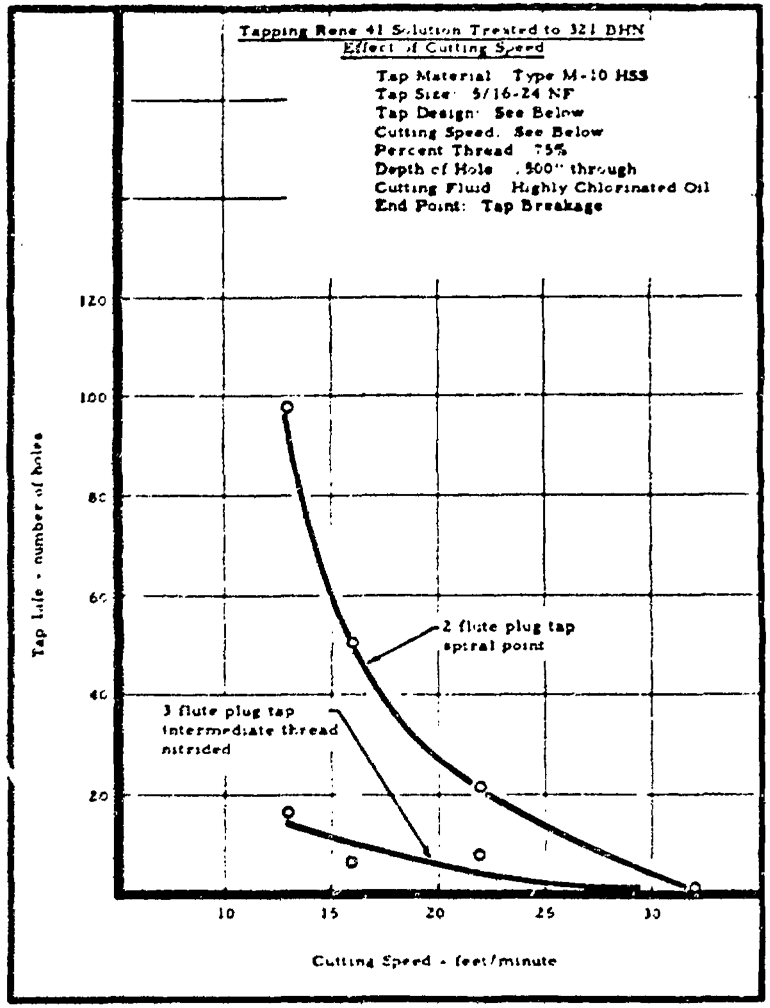

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Figure 245

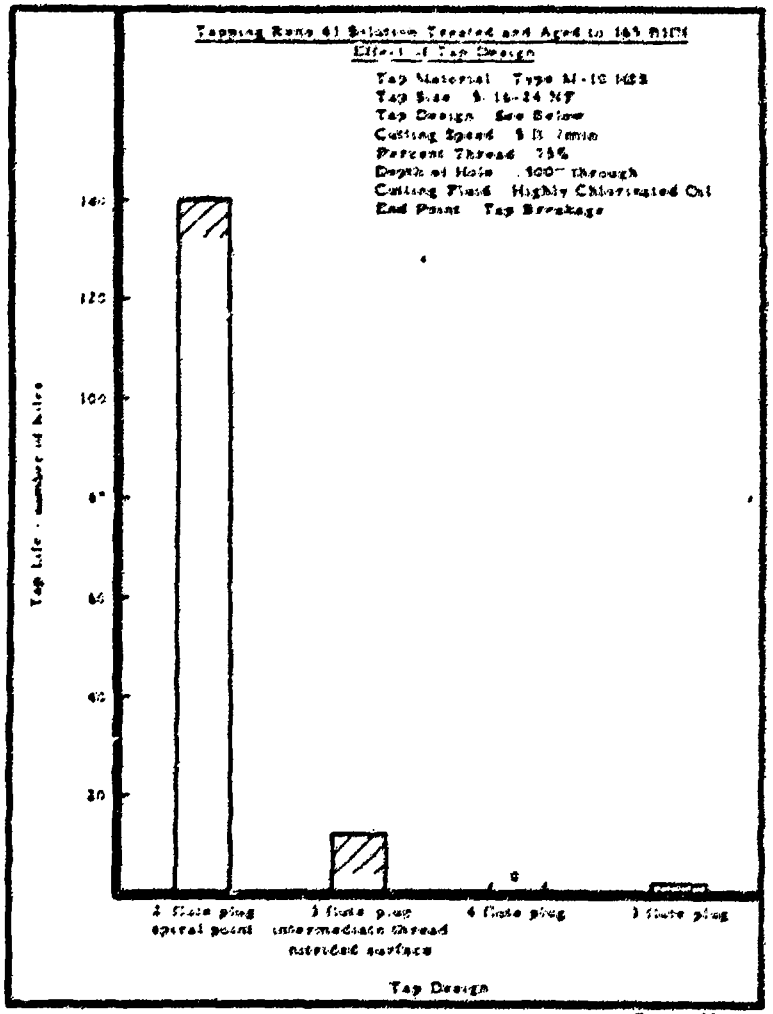

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Figure 246

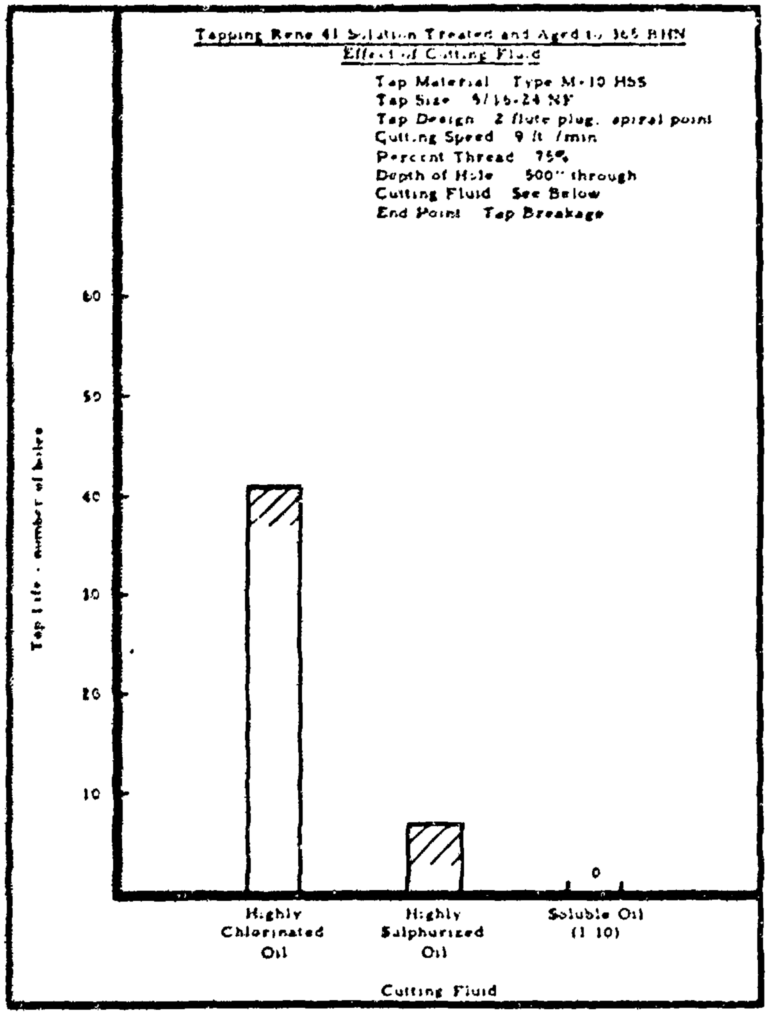

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Figure 247

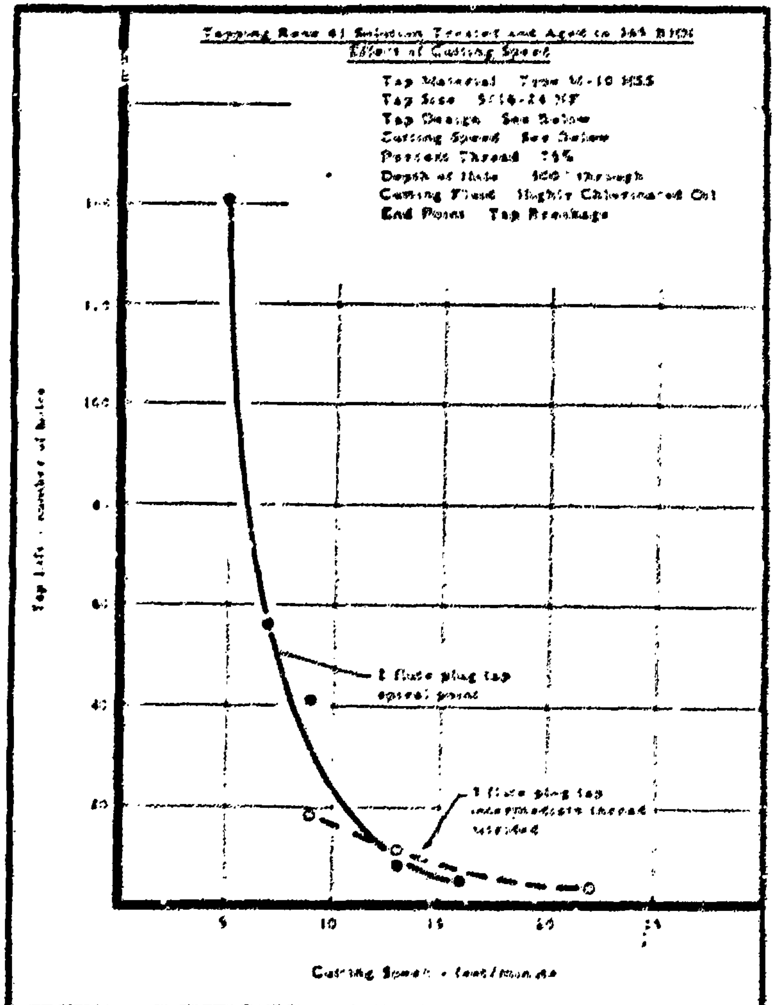

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Figure 248

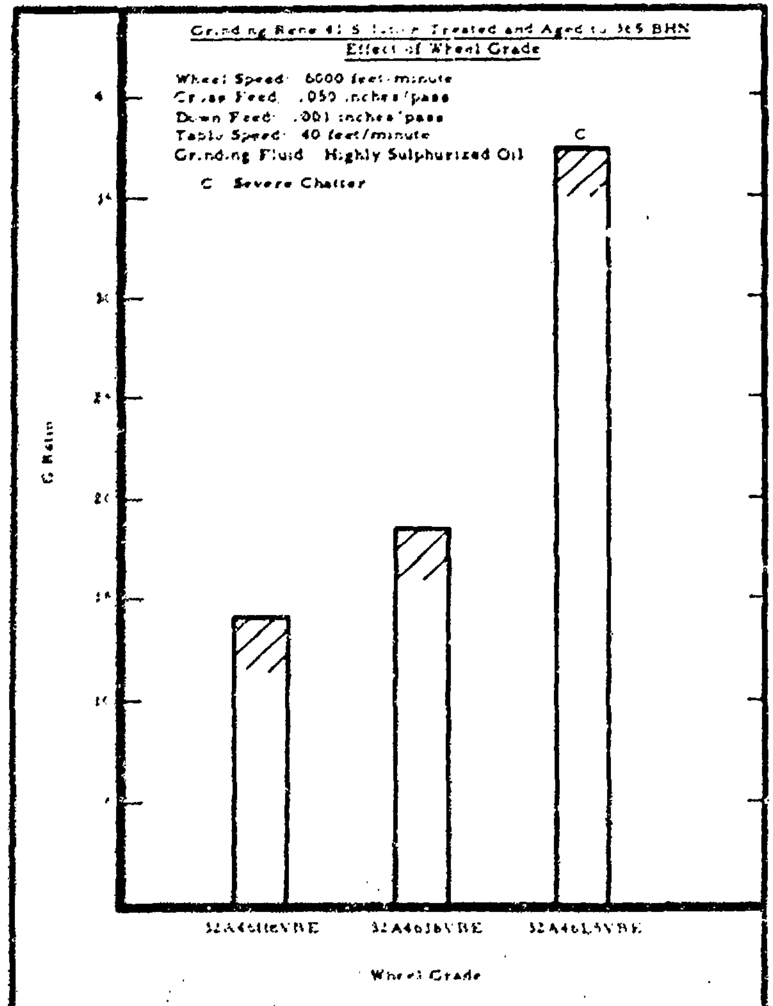

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Figure 249

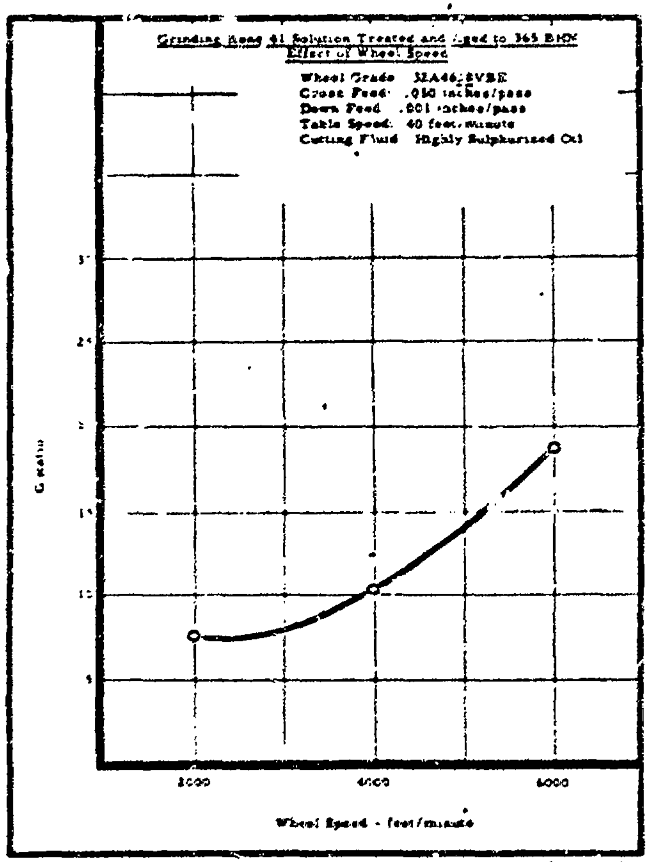

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Figure 250

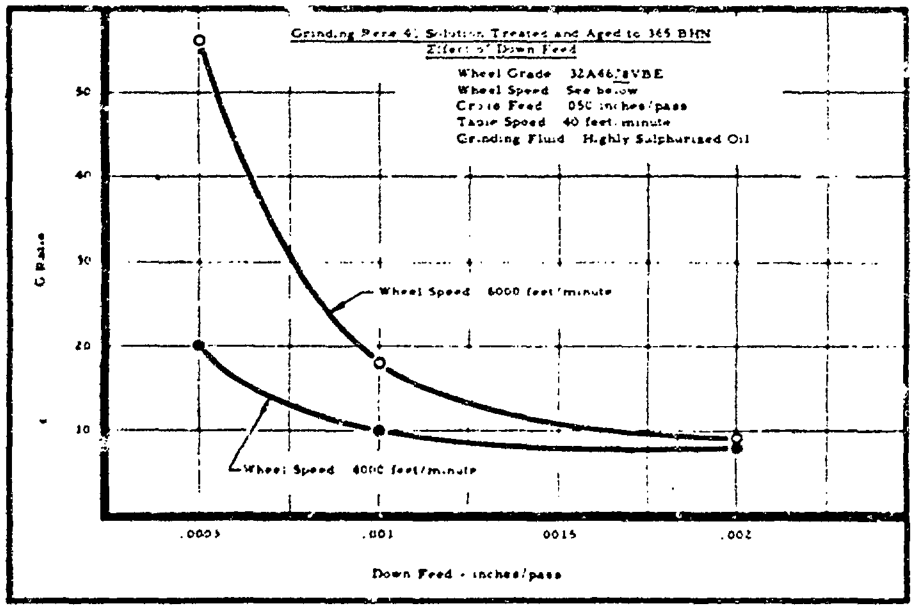

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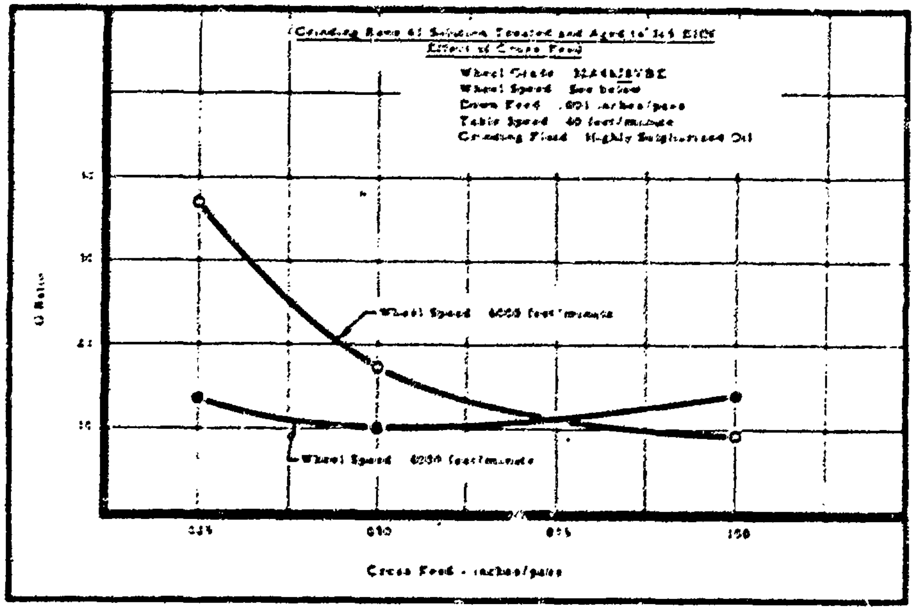
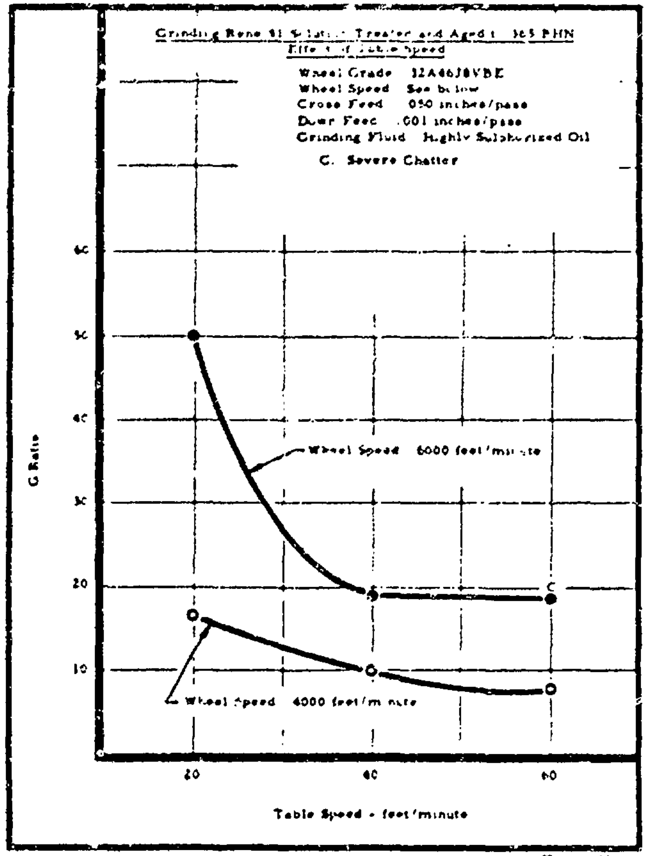
Figure 251



See Text, page 178 Figure 25.



See Text, page 178 Figure 25

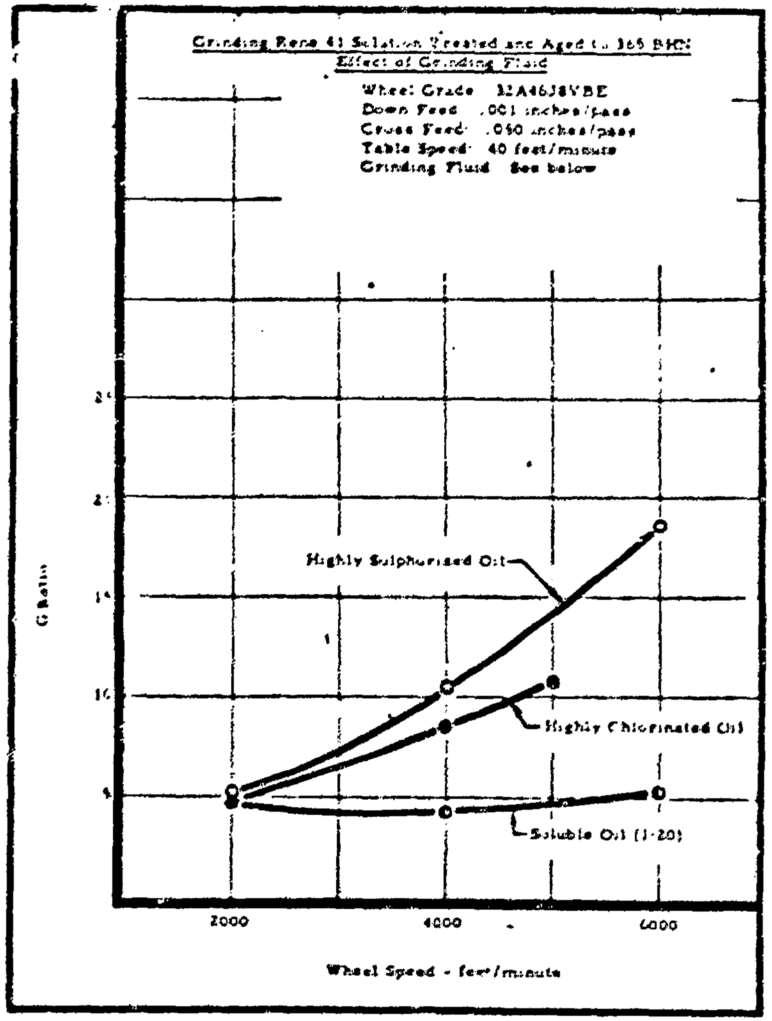


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Figure 254

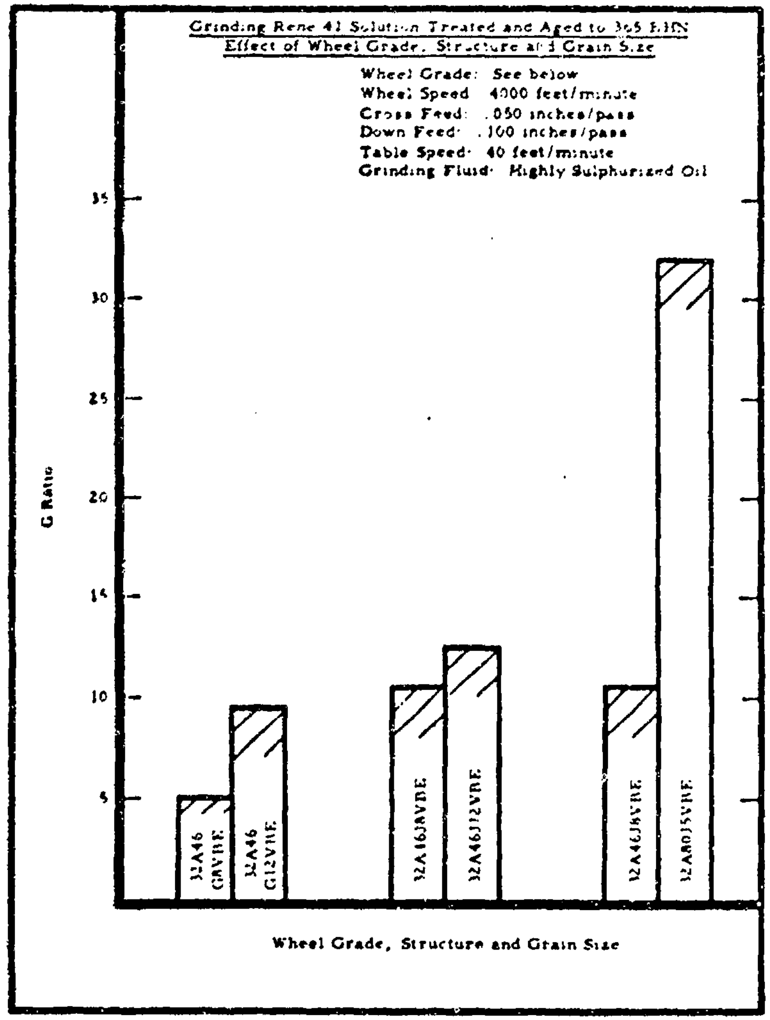

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Figure 255

Since the advent of the missile industry, alloy steels have been used for the production of propellant chambers and other missile components. Advances in design, processing and metallurgy have made feasible the use of steels having minimum tensile strengths of 220,000 to 300,000 psi in these applications. Research and development efforts are now aimed at extending this capability to the 400,000 psi strength level.

D6AC is considered representative of this group of ultra-strength steels. When heat treated to attain the strength levels for which they were designed, these alloys consist primarily of tempered martensite, plus generally small spherical carbides. Microstructures of D6AC steel are shown in Figure 256, page 216. The analysis of the heat studied in this program is presented in Table 16, below:

Table 16

Chemical Composition of D6AC Steel, Percent

	C	Mn	Si	Cr	V	Ni	Mo	Fe
D6AC	.45	.80	.25	1.15	.05	.55	1.0	Bal

Recommendations for Machining D6AC Steel Quenched and Tempered 54-58 R_c

D6AC quenched and tempered to 56-58 R_c cannot be machined with any type high speed steel tool in any machining operation satisfactorily. Very short tool life can be obtained on D6AC at a hardness of 56 R_c with a super high speed steel tool at a very low cutting speed. Carbide tools must be used for a reasonable tool life. Nitrided high speed steel taps can be used to tap D6AC at hardness levels up to 54 R_c.

The machining data for D6AC steel quenched and tempered 54-58 R_c has been reviewed, and general recommendations for machining this alloy at these hardness levels are given in Table 17, pages 217 and 218.

Turning Tests

The results of turning tests on D6AC steel quenched and tempered to 56 R_c using high speed steel, cast alloy, carbide and oxide tools are shown in Figures 257 through 260, pages 219 and 220.

Results of an evaluation of high speed steel and cast alloy tool materials is shown in Figure 257, page 219. Tool life at a cutting speed of 15 feet/minute was less than one minute for T-15 high speed steel and the three grades of

Turning Tests (continued)

cast alloy tool materials. The 12% cobalt Braecut high speed steel, however, produced a seven minute tool life at 15 feet/minute. Tool life for this tool increased to 12 minutes at a cutting speed of 25 feet/minute and then decreased to eight minutes at 40 feet/minute.

The effect of feed on tool life in turning the D6AC steel with carbide is presented in Figure 258, page 219. Note that with the C-4 grade of carbide, tool life in terms of minutes decreased as the feed was increased; however, in terms of cubic inches of metal removed tool life was maximum at a feed of .009 inches per revolution. Nevertheless, lighter feeds are usually used since there is less danger of chipping the carbide at these feeds.

The proper selection of grade of carbide is very important in turning the high strength steels. In Figure 259, page 220, the cutting speeds for equivalent tool life are over twice as great with the C-8 grade as with the C-6 grade. The tool life with the C-8 grade was over 49 minutes at a cutting speed of 95 feet per minute and only 44 minutes at 45 feet/minute with the C-6 grade.

In Figure 260, page 220, a comparison is made between an oxide tool and the best of the various carbide grades tested. The cutting speeds with the oxide tool were 75% greater than those with the carbide tool.

Face Milling Tests

Results of the face milling tests on D6AC steel quenched and tempered to 56 to 58 R_c are shown in Figures 261 through 263, pages 221 and 222.

The position of the cutter relative to the workpiece was found to be an extremely important variable in the face milling of 56 R_c D6AC. Figure 261, page 221, shows a plot of tool life versus cutter-workpiece position for two different cutter geometries. The data indicates that tool life was increased as much as ten times by positioning the workpiece sothat the center of the cutter was 1/2" above the center of the work. For a cutter of 0° AR and -15° RR, tool life was increased from five inches work travel per tooth with the cutter centered on the work, to 55 inches with the cutter positioned 1/2" above the center of the work. For the opposite condition, where the cutter was positioned below the center of the work, tool life was only about one inch work travel per tooth, due to immediate chipping of the carbide tool material. The same effect as described above was produced by a cutter having a 0° AR and 0° RR, except that the effect was not as pronounced. Maximum tool life for this geometry was 43 inches work travel per tooth, compared to 55 inches for the 0° AR, -15° RR geometry.

In view of the results described above, all subsequent face milling tests on D6AC steel were performed using a down milling setup, with the center of the cutter positioned 1/2" above the center of the workpiece.

Face Milling Tests (continued)

Note in Figure 262, page 221, that maximum cutter life was obtained at a feed of .008 in./tooth. When the feed was increased to .010 in./tooth or decreased to .006 in./tooth, cutter life decreased 20 and 40%, respectively.

Tool life curves for both 56 R_c and 58 R_c hardness levels are shown in Figure 263, page 222. Maximum tool life obtained on 56 R_c material was 55 inches work travel per tooth at a cutting speed of 97 feet/minute, using a feed of .008 in./tooth. Maximum tool life for D6AC steel at the 58 R_c hardness level using the same cutter was 25 inches work travel per tooth at a cutting speed of 65 feet/minute. Using the same cutting speed and feed, but changing the cutter geometry to -15° AR and 7° RR, increased tool life to 34 inches work travel per tooth.

Slot Milling Tests

Test results for slot milling D6AC steel quenched and tempered to 56 and 58 R_c are shown in Figures 264 through 268, pages 222 through 224.

The effect of carbide grade on tool life for slot milling 56 R_c D6AC steel is shown in Figure 264, page 222. At a cutting speed of 228 feet/minute and a feed of .003 in./tooth, three different manufacturers' non-ferrous C-2 grade carbides all produced a tool life of 36-40 inches work travel per tooth. The C-6 (370) steel cutting grade produced only 18 inches length of cut.

Figure 265, page 223, shows the effect of tool geometry on tool life. Best results were obtained with a cutter ground with a 5° bi-negative axial rake and a 0° radial rake. Tool life decreased when either the axial rake or radial rake was made more negative.

The effect of cutting fluid is shown in Figure 266, page 223. At a cutting speed of 228 feet/minute and a feed of .003 in./tooth, tool life was 40 inches work travel when cutting dry and only 25 inches when either a highly chlorinated oil or a soluble oil were used.

Figure 267, page 224, shows the effects of cutting speed and feed for both 56 and 58 R_c hardness levels. A 6" diameter, 1" wide, inserted tooth carbide slotting cutter was used for these tests. The tool material was C-2 (HA) grade carbide, and the single tooth was ground with a 5° bi-negative axial rake and 0° radial rake. Depth of cut was .125" and cutting was performed dry. For the 56 R_c material, the maximum tool life of 40 inches work travel per tooth was obtained at a cutting speed of 230 feet/minute and a feed of .003 in./tooth. Tool life decreased for both higher and lower cutting speeds and higher and lower feeds. When the workpiece hardness was increased to 58 R_c, it was necessary to reduce the speed to 125 feet/minute and the feed to .002 in./tooth to obtain a tool life of 48 inches work travel per tooth.

Slot Milling Tests (continued)

Figure 268, page 224, shows the effect of depth of cut and type of setup in slot milling 56 R_c D6AC steel. Using a down milling setup, tool life was 54 inches work travel per tooth for a depth of cut of .062" and decreased to 36 inches for a depth of cut of .125", and only nine inches for a .250" depth of cut. When an up milling setup was used, tool life was only one inch work travel, compared to the 36 inches obtained with a down milling setup and depth of cut of .125".

End Mill Slotting

The results of end mill slotting tests on D6AC steel quenched and tempered to 56 R_c are shown in Figures 269 through 271, pages 225 and 226. These tests were performed using 1-1/4" diameter heavy duty carbide tipped end mills having a shank diameter of 1-1/4" and a flute length of 1".

Figure 269, page 225, shows the effect of cutting fluid and method of application on tool life. Soluble oil applied as a mist through the center of the rotating cutter provided the best tool life. With highly chlorinated oil, the flood application of the cutting fluid gave better results than mist application.

Figure 270, page 225, shows an evaluation of various grades of carbide. Best results were obtained with a C-3 (K-8) carbide. A conventional C-2 grade (883) carbide, however, provided only slightly less tool life than did the C-3. The softer C-1 (44A) carbide wore more rapidly than the C-2 or C-3 grades. The harder C-4 (K-11) and C-6 (370) grades both failed quickly from severe chipping, and provided relatively poor tool life.

Figure 271, page 226, shows the effect of cutting speed and feed for slot milling D6AC steel at a hardness of 56 R_c. A grade C-2 (883) carbide was used for these tests, and the cutters were ground with a 0° AR and 0° RR. Depth of cut was .125". The maximum tool life of 54 inches work travel was obtained at a cutting speed of 37 feet/minute when using a feed of .003 in./tooth. For a feed of .002 in./tooth, a tool life of 45 inches was obtained at a cutting speed of 37 feet/minute. Tool life decreased for cutting speeds higher and lower than 37 feet/minute. For a feed of .001 in./tooth, tool life was 36 inches work travel at a cutting speed of 72 feet/minute and decreased at both higher and lower speeds. These tests indicate the best results will be obtained for end milling this material by using a low speed of about 37 feet/minute and a feed of about .003 in./tooth.

Drilling

Tool life curves for drilling D6AC steel at 56 R_c and 58 R_c are shown in Figure 272, page 226. These tests were performed using .272" diameter straight flute,

Drilling (continued)

carbide tipped die drills and a highly chlorinated cutting oil. The data shows that best results for both hardness levels were obtained when using a feed of .001 in./rev. and a cutting speed of 117 feet/minute. Drill life for the D6AC steel at these conditions was 72 holes for the 56 R_c hardness and 40 holes at 58 R_C. Drill life decreased as cutting speed was decreased when using a feed of .001 in./rev. When using a feed of .002 in./rev., drill life increased with decreasing cutting speeds. However, even at a cutting speed of 65 feet/minute when a reasonable drill life was obtained excessive heat and chip clogging were produced and results were generally unsatisfactory.

Reaming

The results of reaming tests on D6AC steel quenched and tempered to 56 R_C are shown in Figures 273 thru 275, pages 227 and 228. Straight shank, 4 flute, .272" diameter reamers tipped with C-2 (883) carbide were used for these tests. Holes were .500" deep through holes and stock removal was .020" from the hole diameter.

Figure 273, page 227, shows a comparison of tool life using two different cutting fluids. At a cutting speed of 65 feet/minute and a feed of .002 in./rev., 60 holes were obtained with a highly chlorinated oil cutting fluid and only 30 holes with a soluble oil diluted with water at a ratio of 1:20.

Figure 274, page 227, indicates the effect of reamer grind on tool life. At a cutting speed of 65 feet/minute and a feed of .002 in./rev., a standard carbide tipped reamer without a negative land chipped severely on the tooth corners after only five holes. This chipping was eliminated and reamer life was increased to 60 holes by honing the corners to produce a land approximately .010" wide having a -5° axial and radial rake.

Figure 275, page 228, shows the effect of cutting speed and feed on reamer life. Using a feed of .001 in./rev., the maximum reamer life for a .012" wearland was only 25 holes at a cutting speed of 60 feet/minute. A significant increase in reamer life was obtained by increasing the feed to .002 in./rev. The maximum life of 60 holes was obtained at a cutting speed of 65 feet/minute. All other cutting conditions being held constant, reamer life decreased at higher and lower cutting speeds. In order to obtain this high reamer life at .002 in./rev. feed, however, it was necessary to hone a small negative rake land at the corner of each of the reamer teeth in order to prevent chipping of the teeth at this point.

Tapping

High speed steel taps cannot be used to tap D6AC at hardness levels above 54 R_C. At a hardness level of 52 to 54 R_C, the high speed steel tap must be nitrided.

Tapping (continued)

Figure 276, page 228, shows the effect of cutting fluid in tapping this alloy at 54 R_c. The most effective cutting fluid was a highly chlorinated oil mixed with inhibited trichloroethane (2:1). A tap life of 16 holes was obtained at a cutting speed of 5 feet/minute with this fluid. Tap life decreased to 12 holes when a highly chlorinated or highly sulphurized oil was used.

The effect of workpiece hardness in tapping D6AC steel at 52 R_c and 54 R_c is shown in Figure 277, page 229. A tap life of 60 holes was obtained in the 52 R_c material, while only 16 holes could be tapped in the 54 R_c hardness material. These tests were performed with a 5/16-24 NF, 4 flute nitrided plug tap operating at 5 feet/minute. The cutting fluid used was a highly chlorinated oil mixed with inhibited trichloroethane (2:1).

In tapping D6AC steel quenched and tempered to 54 R_c, it is possible to increase tap life significantly by decreasing the percent of thread, see Figure 278, page 229. When tapping a 65% thread at 5 feet/minute, 24 holes were obtained. At the same cutting speed, 16 holes were tapped with a 75% thread. When the cutting speed was increased to 9 feet/minute and a 65% thread was used, tap life decreased to 15 holes; and at a tapping speed of 12 feet/minute, only five holes could be tapped.

Surface Grinding Tests

Surface grinding data on D6AC steel quenched and tempered to 56 R_c are presented in Figures 279 through 285, pages 230 through 233.

The effect of wheel grade and wheel speed on grinding ratio is shown in Figure 279, page 230. A down feed of .001 in./pass and a soluble oil grinding fluid were used for these tests. All grinding wheels used for these tests were manufactured from grade 32 aluminum oxide, 46 grit size, vitrified bond. Five wheels were tested with hardness and structure ranging from G8 to N5. Each wheel was tested at 2000, 4000 and 6000 surface feet/minute. The data indicates that for the G8, I8 and J8 wheel grades the G ratio increased as wheel speed was increased from 2000 to 6000 feet/minute. G ratio at 6000 feet/minute was 20 for the G8 wheel and 60 for both the I8 and J8 wheels. An extremely low G ratio of two was obtained with the G8 wheel at 2000 feet/minute wheel speed. The maximum G ratio obtained in these tests was 95 when using a 32A46N5VBE wheel at 2000 feet/minute. The G ratio decreased to 40, however, when this wheel was run at 4000 and 6000 feet/minute. Severe chatter and surface cracking were produced by this wheel at 6000 feet/minute. When the H8 wheel was used, G ratio increased from 40 at 2000 feet/minute to 64 at 4000 feet/minute, then decreased again to 48 as the wheel speed was increased to 6000 feet/minute.

Surface Grinding Tests (continued)

Figure 280, page 230, shows G ratio curves for three wheel grades when using a .002 in./pass down feed. At a wheel speed of 6000 feet/minute, G ratio was 20 for an H8 wheel and 52 for an J8 wheel. Chatter and surface cracking were produced by the N5 wheel at 6000 feet/minute and G ratio was 43.

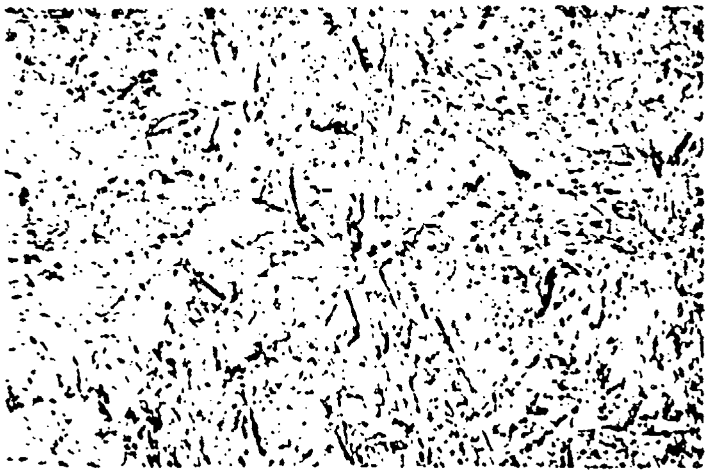
Figure 281, page 231, shows a plot of G ratio versus wheel hardness for .001 and .002 in./pass down feeds. Using .001 in./pass, the G ratio increased from 28 for a "G" hardness wheel to 72 as hardness was increased to an "I" hardness wheel, then decreased to 40 as hardness of the grinding wheel was further increased to "N". The same type of data was produced for the heavier down feed of .002 in./pass.

The effect of down feed on G ratio when using a 32A46J8VBE wheel and soluble oil grinding fluid is shown in Figure 282, page 231. Down feeds of .001, .002 and .003 in./pass were used. For all three feeds, G ratio increased fairly uniformly as wheel speed was increased from 2000 up to 6000 feet/minute. At the 6000 feet/minute wheel speed, G ratio was 68 for .001 in./pass down feed, 52 for .002 in./pass and 32 for .003 in./pass.

Figure 283, page 232, shows the effect of table speed on G ratio. When using a J8 grade wheel, G ratio increased from 33 at 20 feet/minute table speed to 59 at 40 feet/minute, then decreased to 32 when the table speed was increased to 60 feet/minute.

The effect of cross feed is shown in Figure 284, page 232. G ratio increased with increased cross feed from 42 at .025 in./pass to 100 at .100 in./pass cross feed. However, chatter and severe surface cracking were produced at the .100 in./pass cross feed.

The effect of grinding fluid is shown in Figure 285, page 233. A 32A46J8VBE wheel at 6000 feet/minute and a down feed of .002 in./pass were used for these tests. Maximum G ratio of 90 was obtained when a highly sulphurized oil was used as a grinding fluid. A highly chlorinated oil produced a G ratio of 58, while with a soluble oil mixed 1:20 with water, the G ratio was 52.



Optical Photomicrograph
Quenched and Tempered, 56 R_c
Microstructure is fully martensitic.
Magnification: 1000X Etchant: Nital

Electron Photomicrograph
Quenched and Tempered, 56 R_c
Microstructure shows start of formation of free carbides.
Magnification: 8000X Etchant: Nital

Figure 256

See Text, page 209

TABLE 17
RECOMMENDED CUTTING CONDITIONS FOR MACHINING
D6AC STEEL QUENCHED AND TEMPERED TO 56 R_c AND 58 R_c

Nominal Chemical Composition, Percent

C	Mn	Si	Cr	V	Ni	Mo	Fe
.45	.80	.25	1.15	.05	.55	1.0	Bal.

Operation & Workpiece Hardness	Tool Material	Tool Geometry	Tool Used for Tests	Depth of Cut inches	Width of Cut inches	Feed	Cutting Speed ft./min.	Tool Life	Wear-land inches	Cutting Fluid
Turning 56 R_c	C-4 Carbide	BR: -5° SCEA: 15° SR: -5° ECEA: 15° Relief: 5° NR: 1/32"	1/2" square throwaway holder with mech. chip breaker	.062	-	.005 in/rev	75	38 min.	.016	None
Turning 56 R_c	030 Ceramic	BR: -5° SCEA: 15° SR: -5° ECEA: 15° Relief: 5° NR: 1/32"	1/2" square throwaway holder with mech. chip breaker	.062	-	.005 in/rev	175	26 min.	.016	None
Face Milling 56 R_c Down Milling Setup	C-2 Carbide	AR: 0° ECEA: 6° RR: -15° Clearance: 10° CA: 45°	4" diameter face mill	.060	2	.010 in/tooth	65	65 in/tooth	.016	None
Face Milling 58 R_c Down Milling Setup	C-2 Carbide	AR: 0° ECEA: 6° RR: -15° Clearance: 10° CA: 45°	4" diameter face mill	.060	2	.008 in/tooth	65	25 in/tooth	.016	None
Slot Milling 56 R_c Down Milling Setup	C-2 Carbide	AR: -5° bi-negative RR: 0° ECEA: 1° CA: 45° x .030" Clearance: 10°	6" dia. x 1" wide inserted tooth slotting cutter	.125	1	.003 in/tooth	230	40 in/tooth	.020	None
Slot Milling 58 R_c Down Milling Setup	C-2 Carbide	AR: -5° bi-negative RR: 0° ECEA: 1° CA: 45° x .030" Clearance: 10°	6" dia. x 1" wide inserted tooth slotting cutter	.125	1	.002 in/tooth	125	48 in/tooth	.020	None

See Text, page 209

TABLE 17

RECOMMENDED CUTTING CONDITIONS FOR MACHINING D6AC STEEL QUENCHED AND TEMPERED TO 56 R_c AND 58 R_c

Operation & Workpiece Hardness	Tool Material	Tool Geometry	Tool Used for Tests	Depth of Cut inches	Width of Cut inches	Feed	Cutting Speed ft/min	Tool Life	Wear-land inches	Cutting Fluid
End Mill Slotting 56 R_c	C-2 Carbide	AR: 0° ECEA: 5° RR: 0° Clearance: 15° CA: 45° x .030"	1-1/4" dia., 4 flute heavy duty, brazed tip end mill	.125	1-1/4	.003" per tooth	40	54 inches	.016	(1) Soluble Oil (1:20)
Drilling 56 R_c	C-2 Carbide	Point Angle: 118° Helix Angle: 0° Clearance: 10° Notched Point	.250" dia. carbide tipped die drill	1/2" thru hole	-	.001" per rev.	115	70 holes	.016	Highly Chlorinated Oil
Drilling 58 R_c	C-2 Carbide	Point Angle: 118° Helix Angle: 0° Clearance: 10° Notched Point	.250" dia. carbide tipped die drill	1/2" thru hole	-	.001" per rev.	115	40 holes	.016	Highly Chlorinated Oil
Reaming 56 R_c	C-2 Carbide	Helix Angle: 0° (2) Corner Angle: 45° Clearance: 10°	Standard .272" dia. 4 flute carbide tipped chucking reamer	1/2" thru hole	-	.002" per rev.	65	60 holes	.012	Highly Chlorinated Oil

SURFACE GRINDING

Wheel Grade	Grinding Fluid	Wheel Speed feet/minute	Table Speed feet/minute	Down Feed inches/pass	Cross Feed inches/pass	G Ratio
32A46H8VBE	Highly Sulphurized Oil	6000	40	.001	.050	75

(1) Applied as spray mist through axis of cutter

(2) 5° negative rake land honed on tooth corners approximately .010" wide

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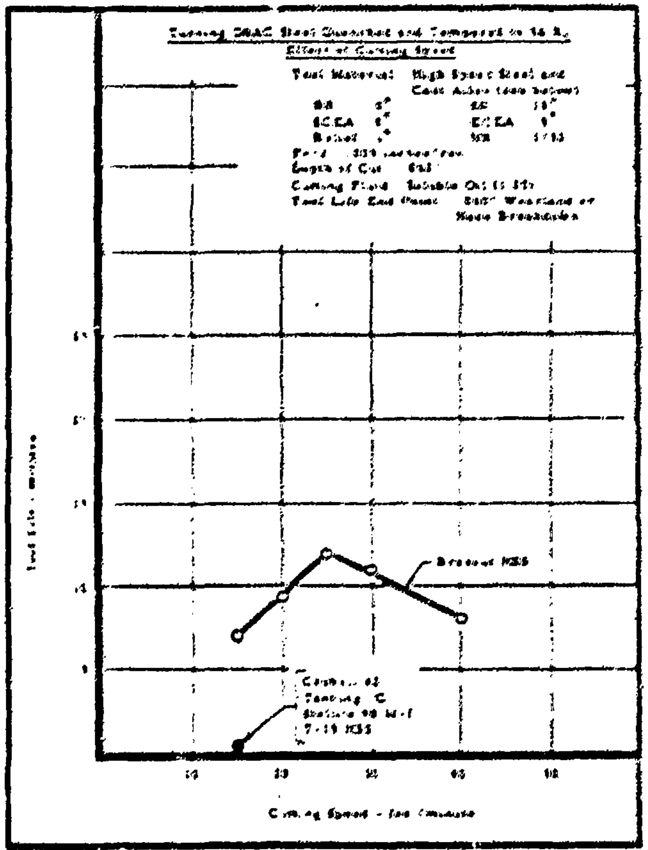

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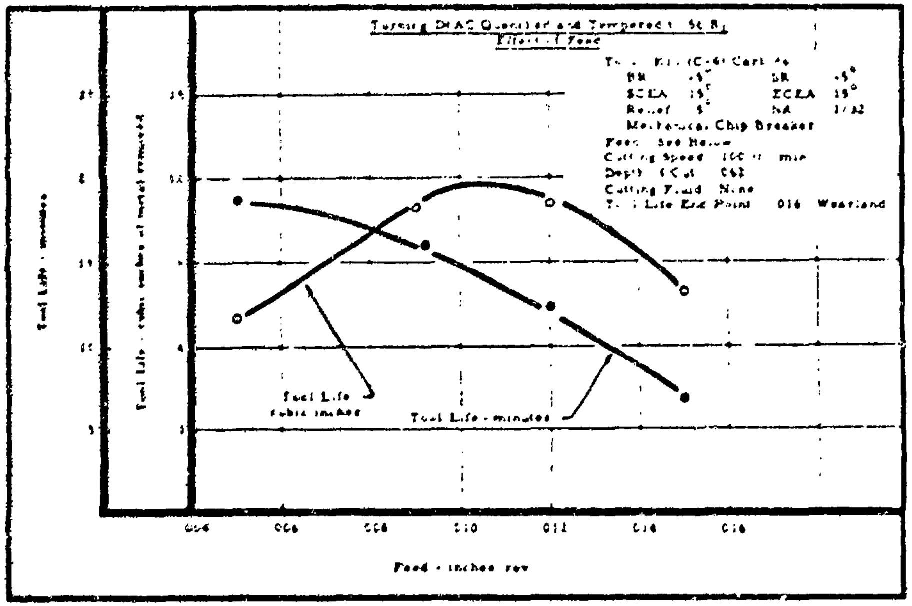

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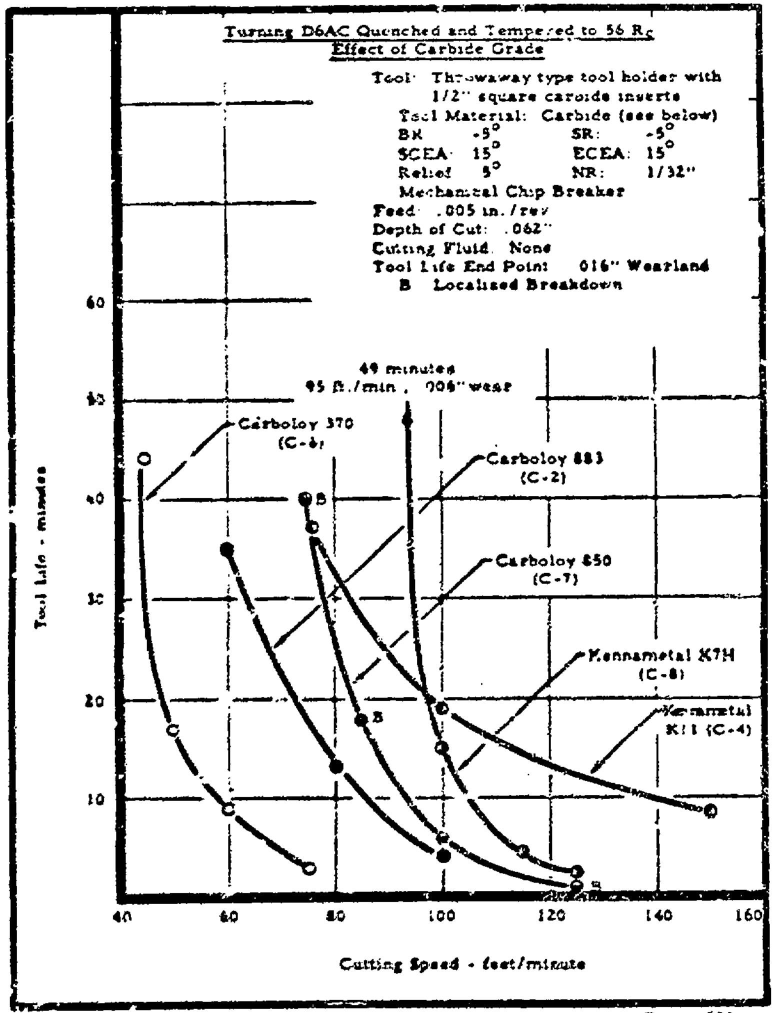

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Figure 259

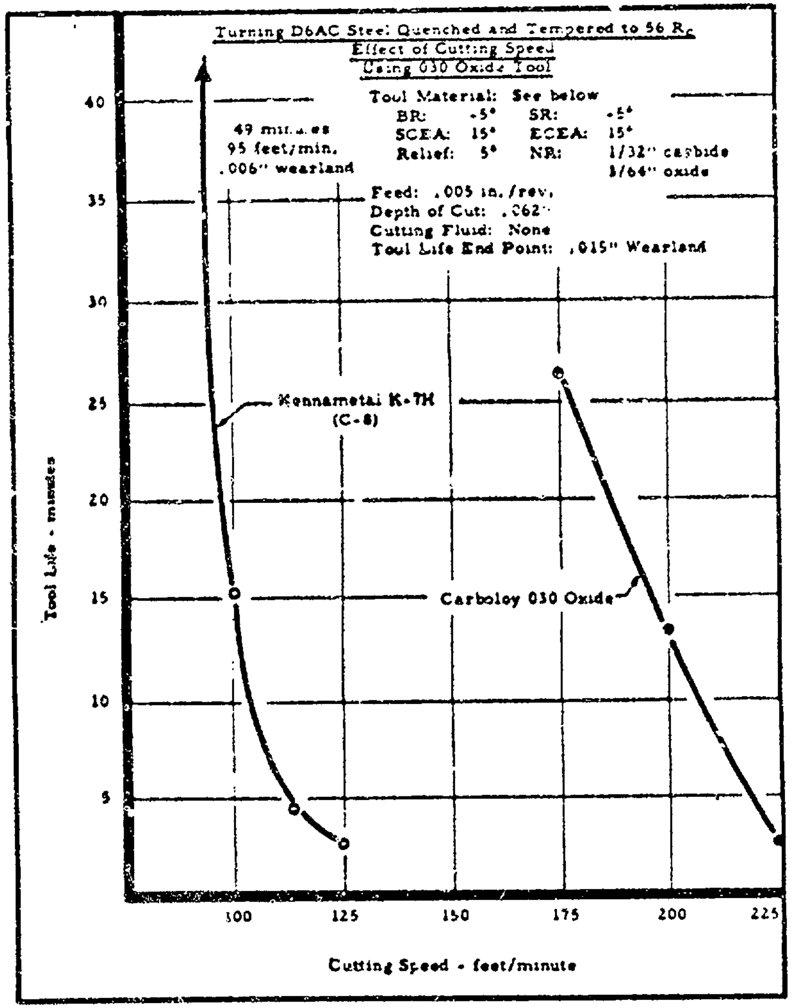

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Figure 260

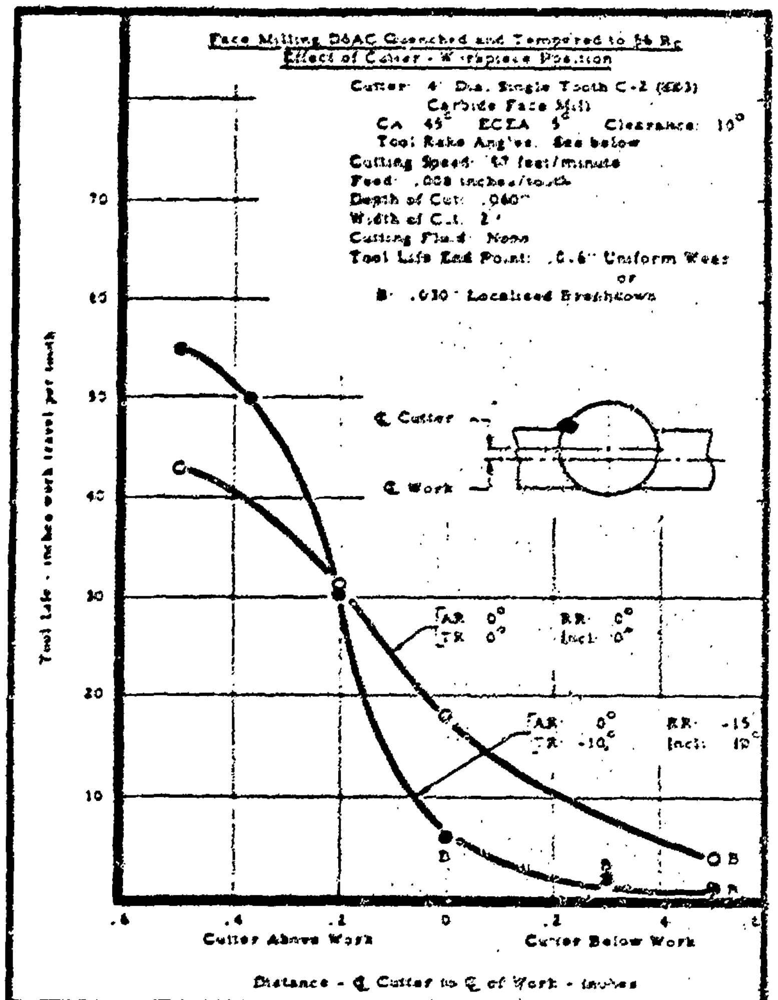

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Figure 261

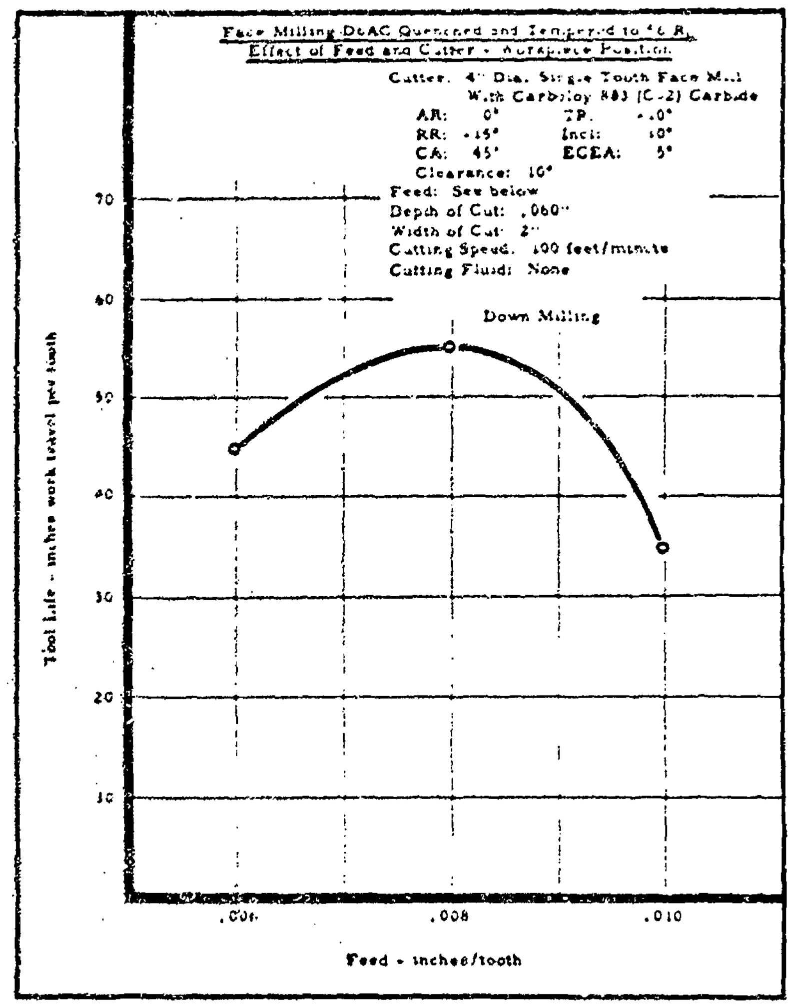

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Figure 262

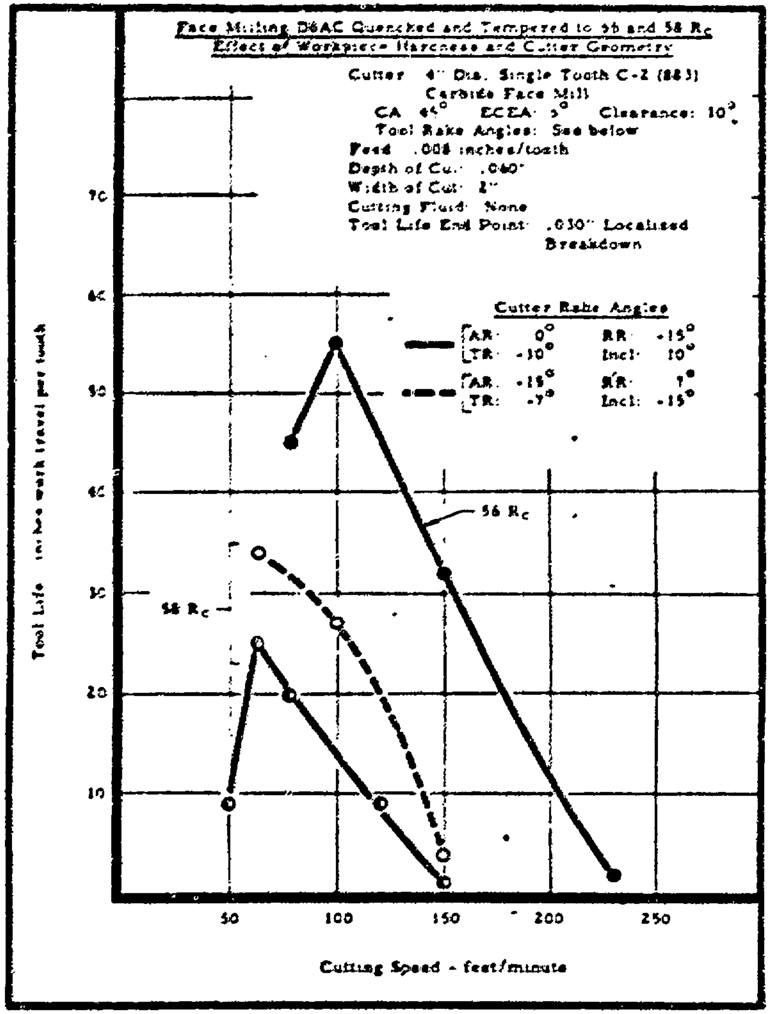

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Figure 263

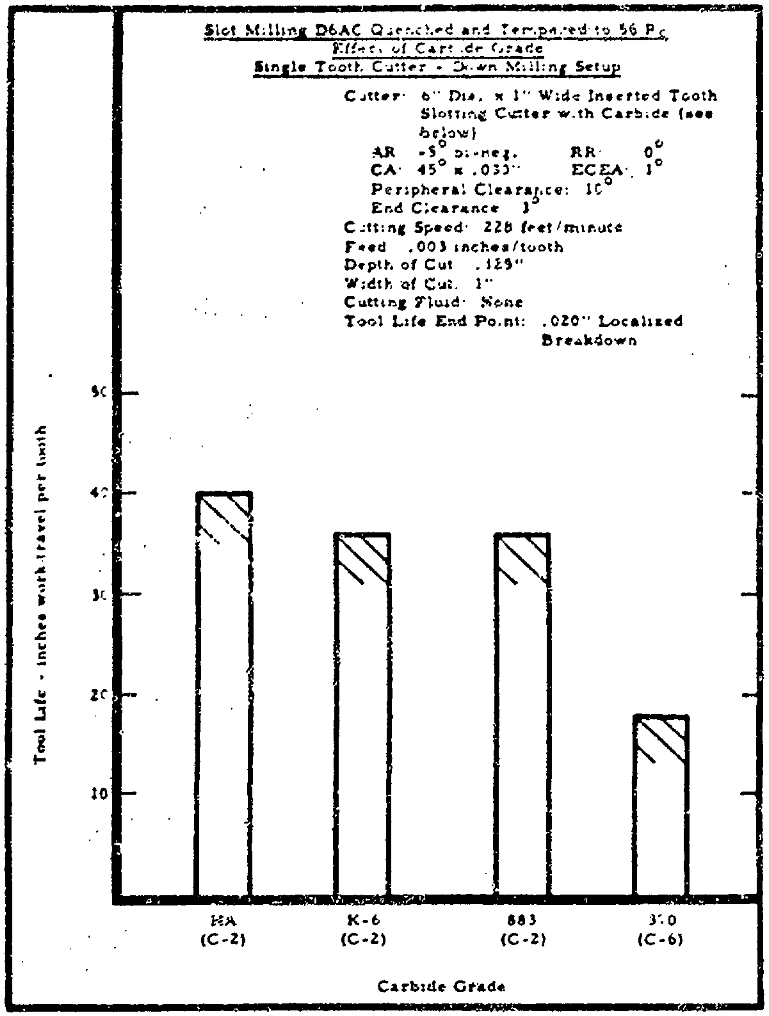

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Figure 264

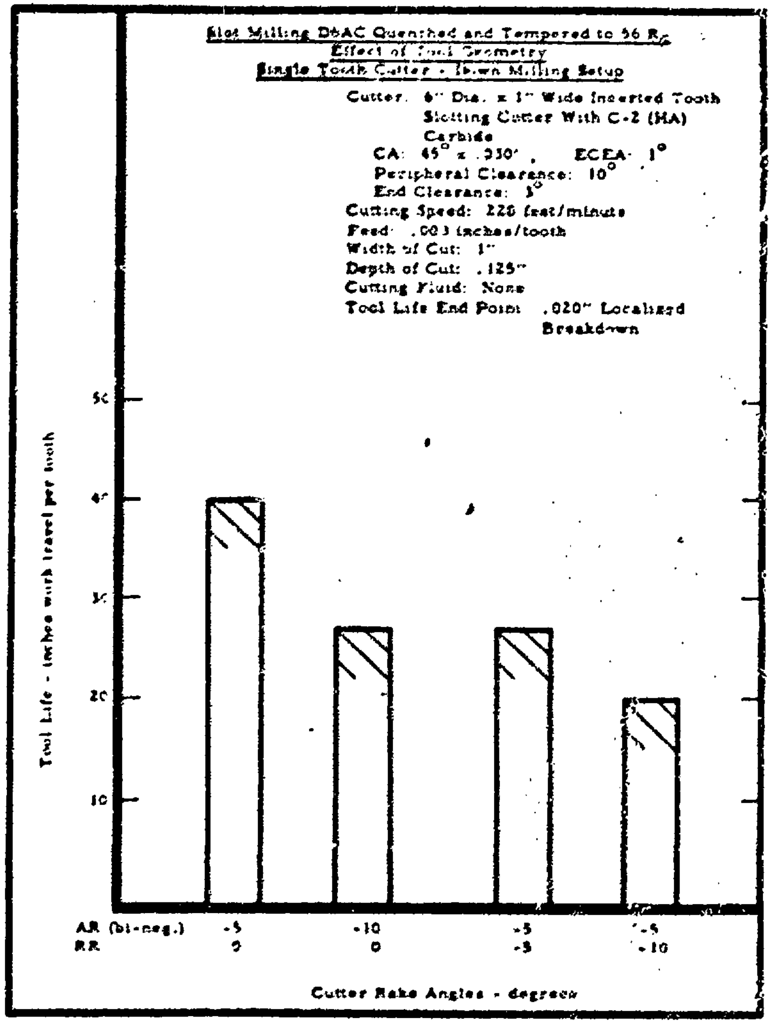

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Figure 265

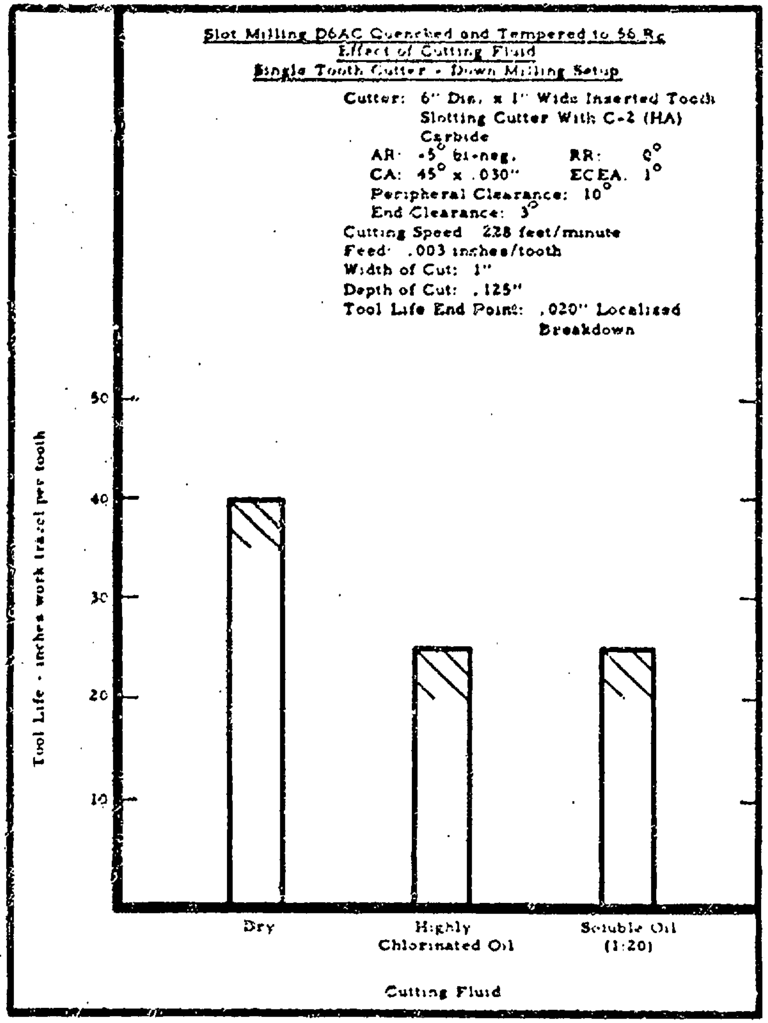

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Figure 266

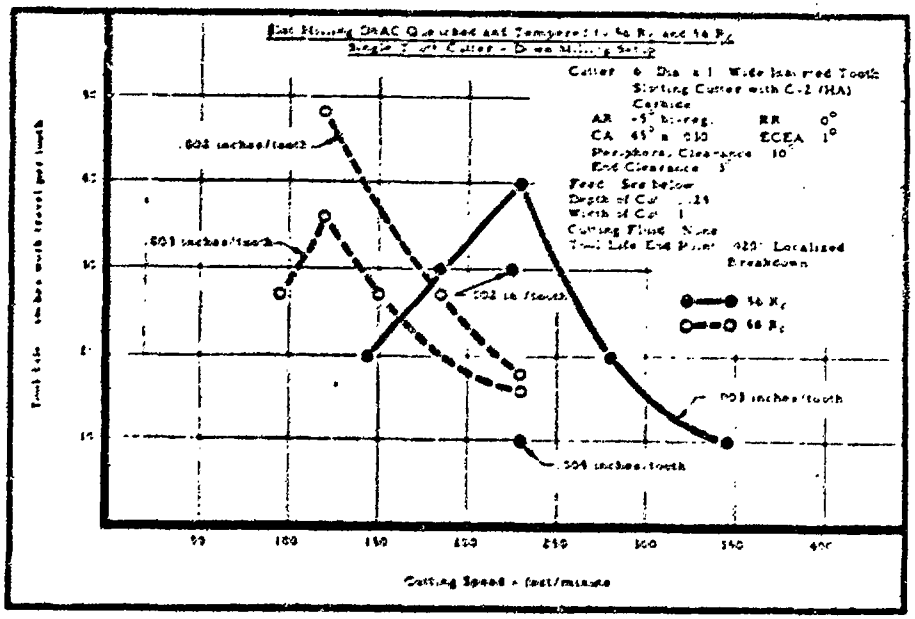

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Figure 267

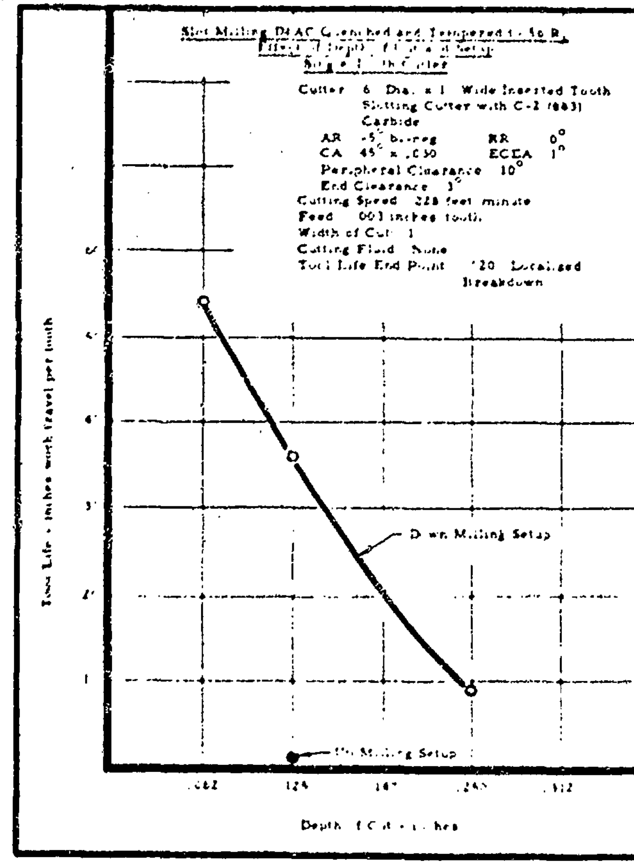

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Figure 268

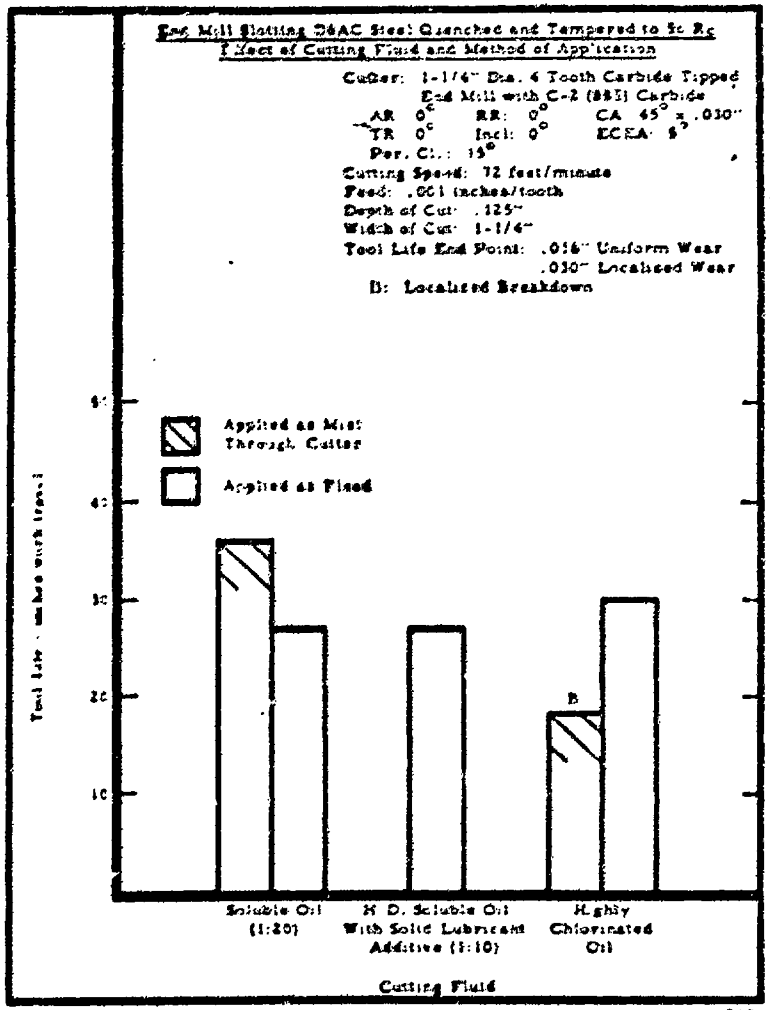

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Figure 269

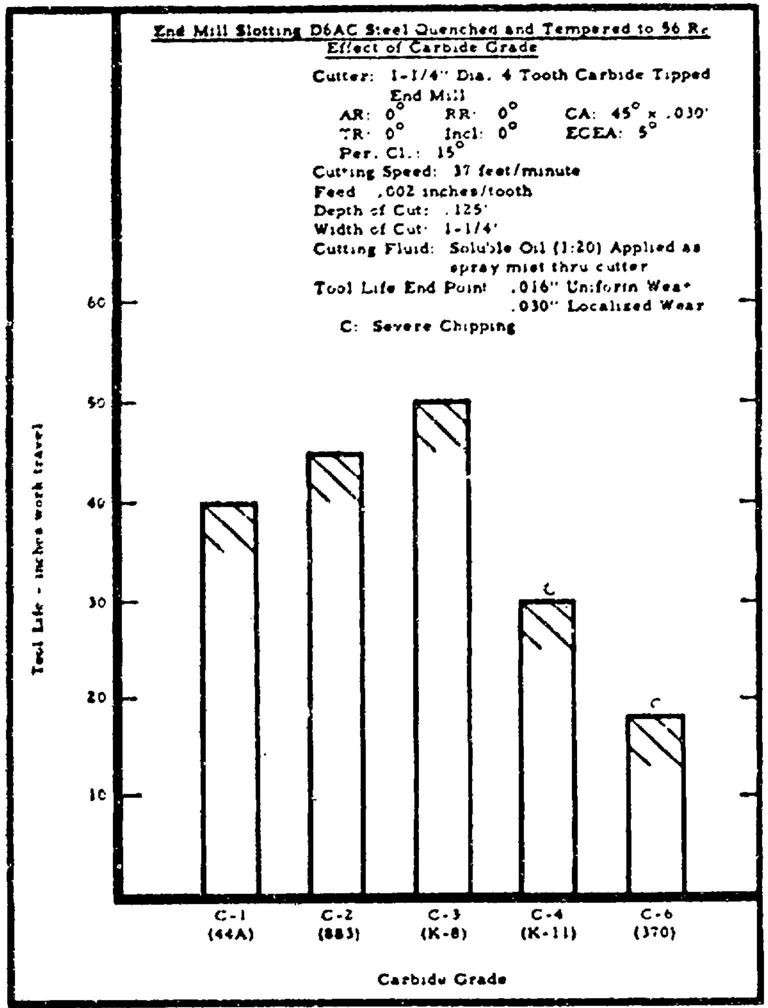

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Figure 270

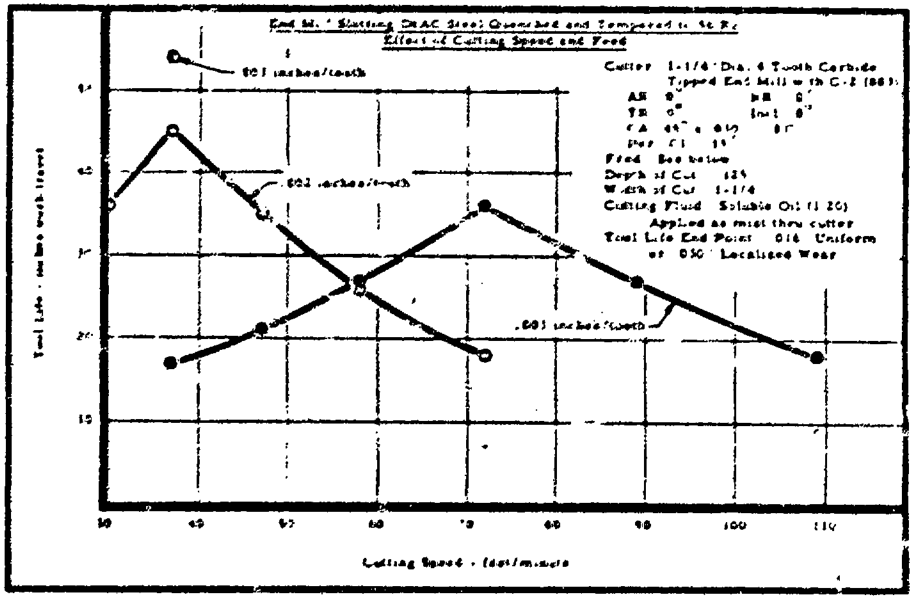

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Figure 271

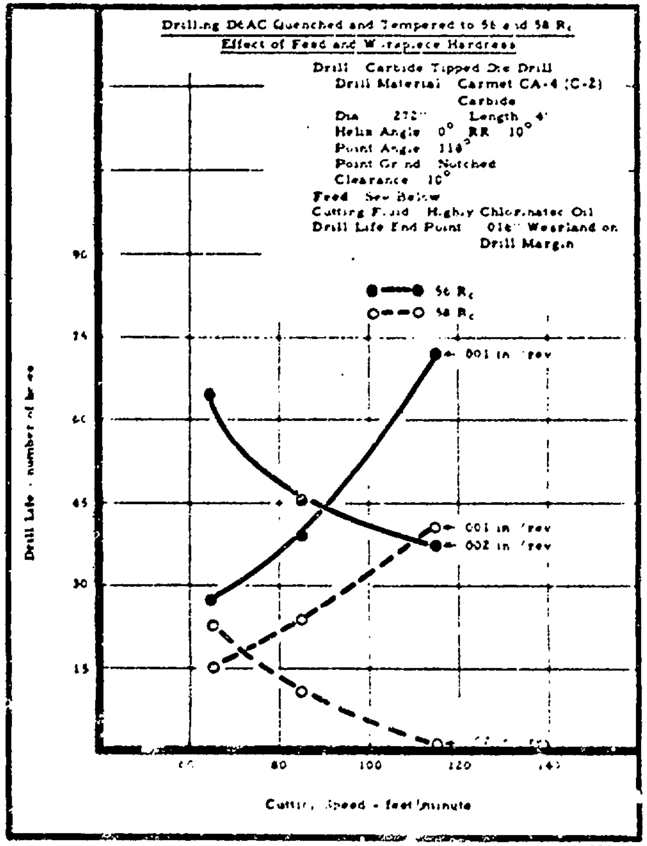

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Figure 272

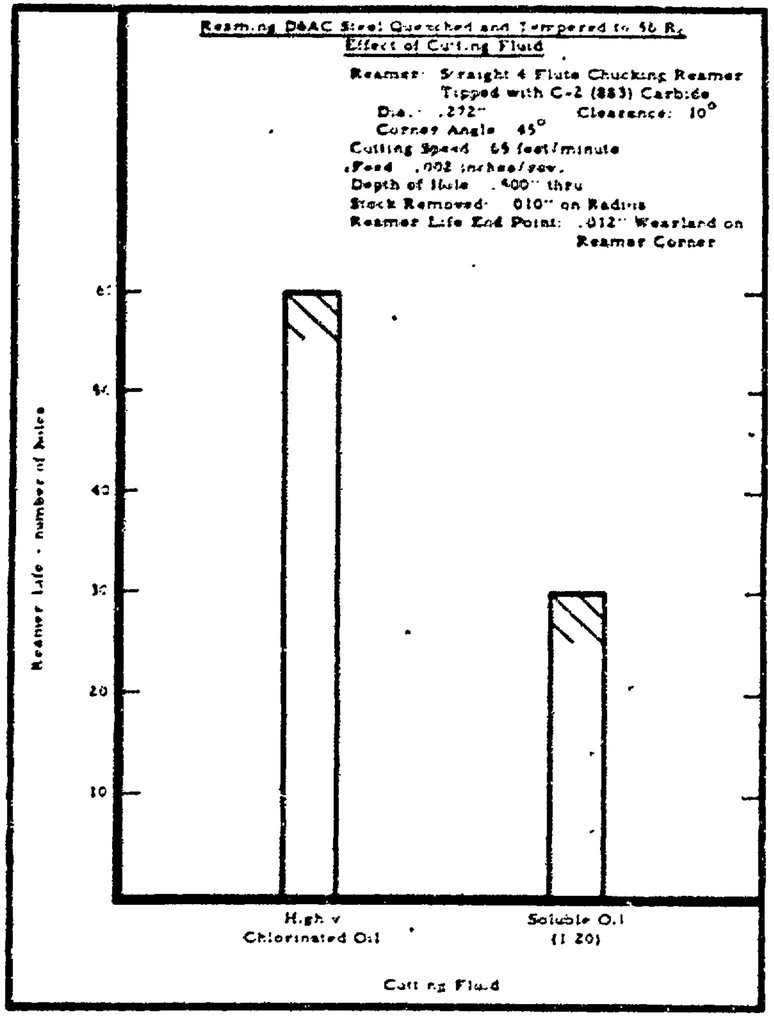

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Figure 273

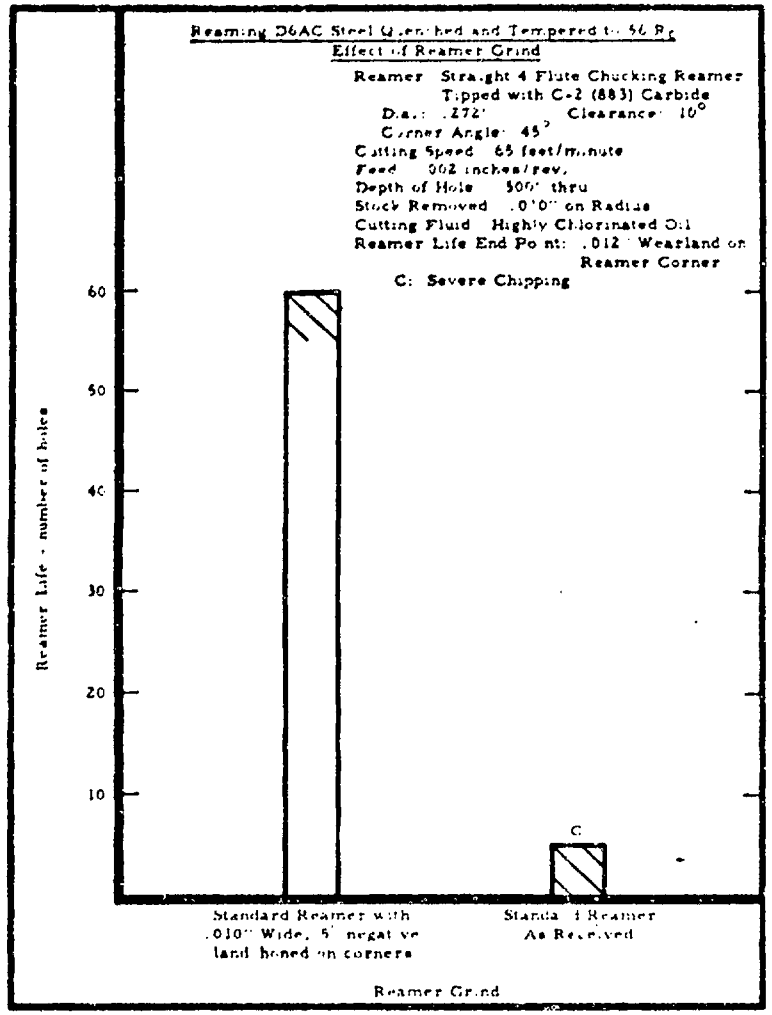

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Figure 274

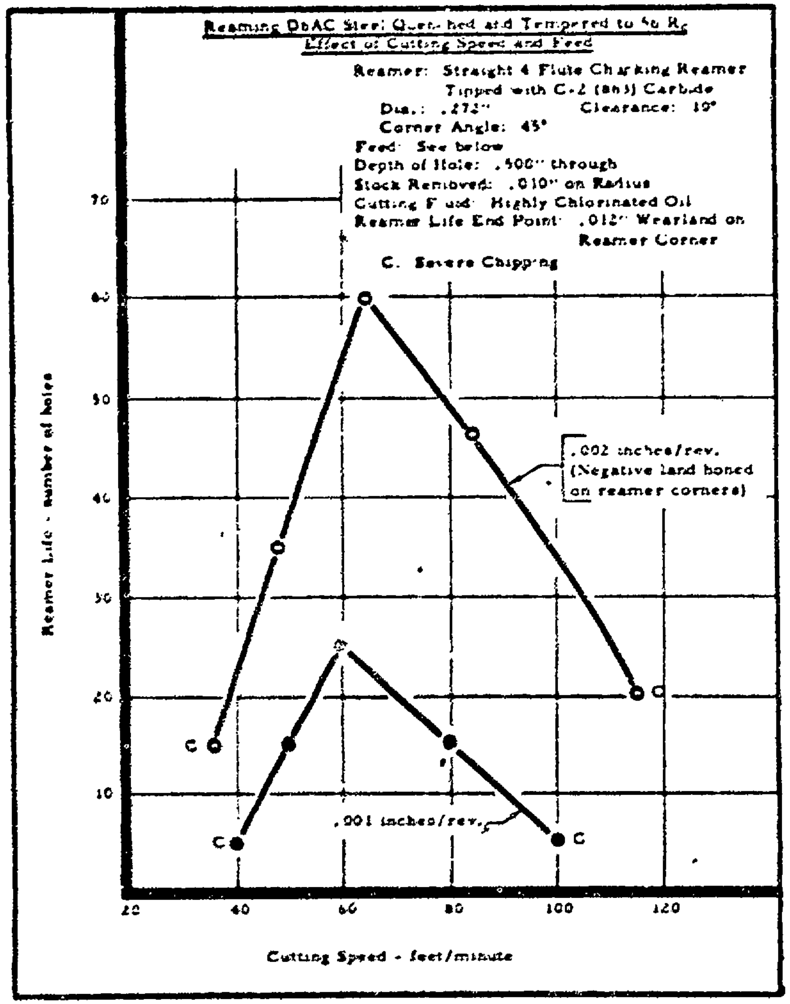

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Figure 275

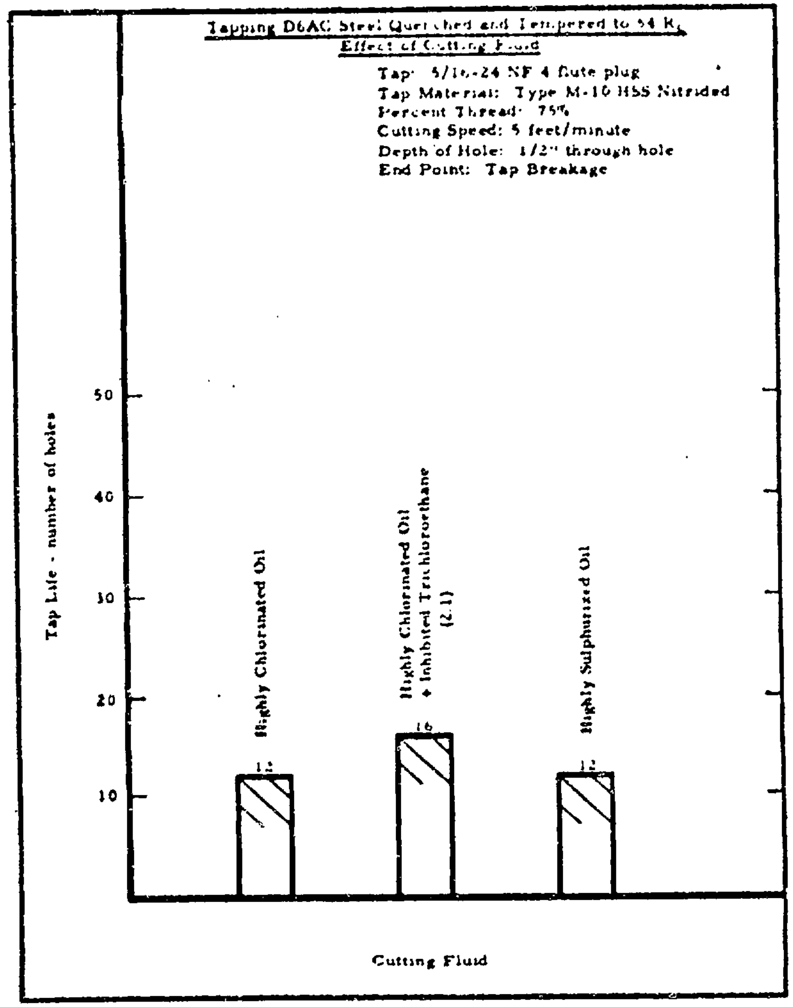

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Figure 276

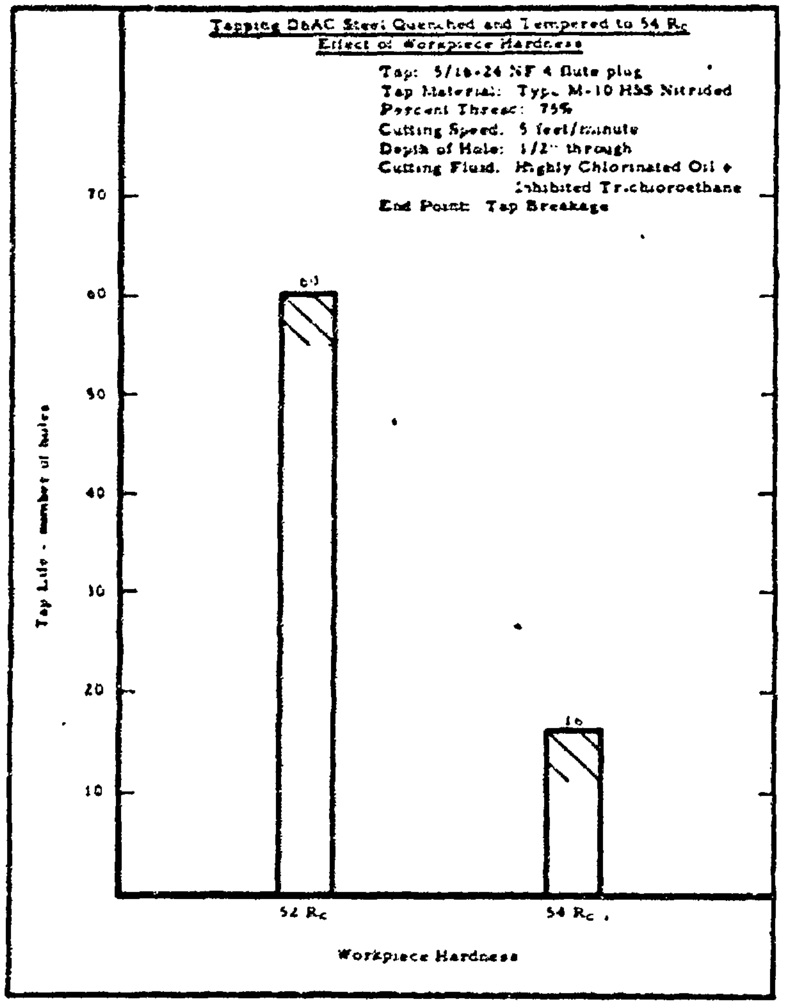

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Figure 277

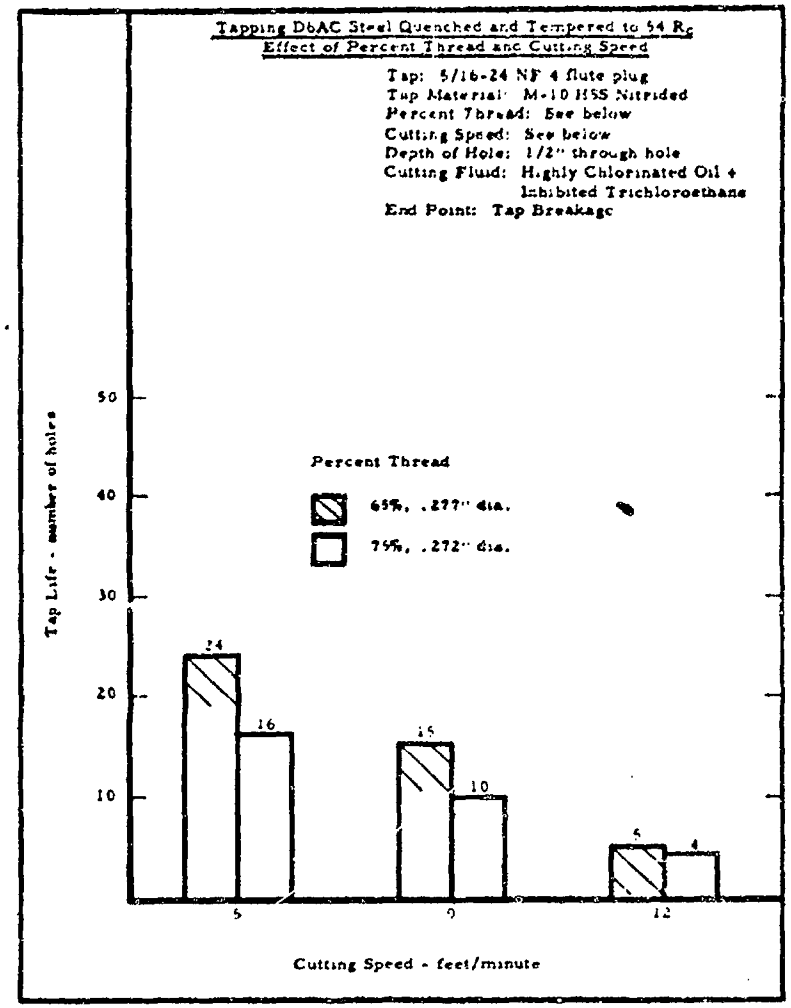

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Figure 278

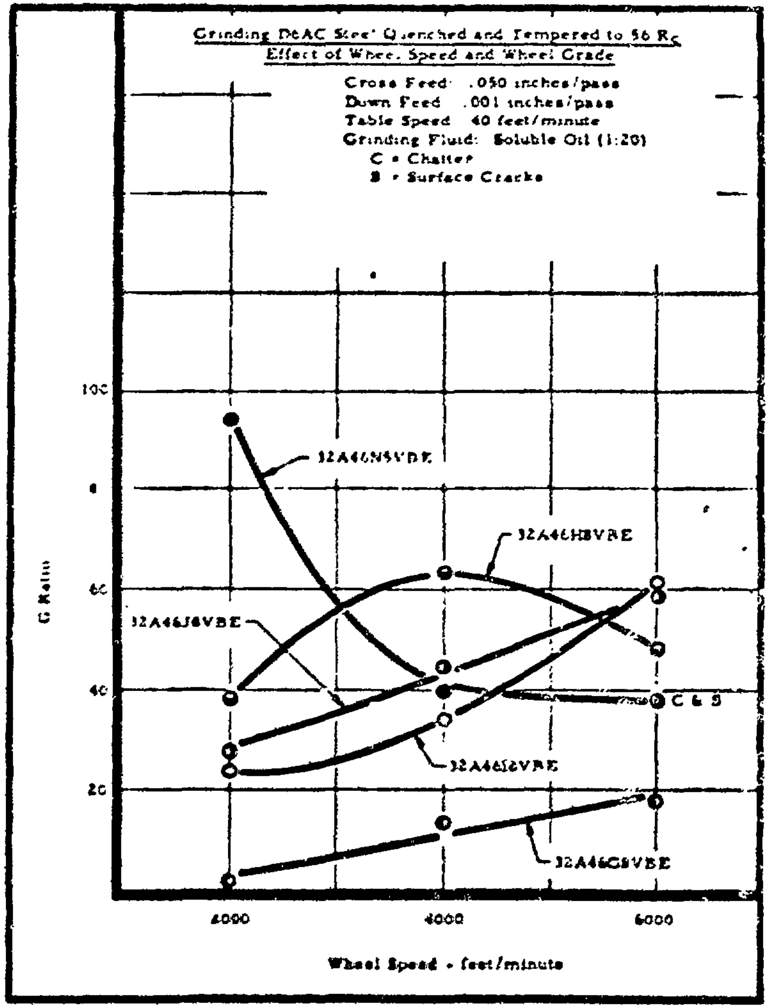

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Figure 279

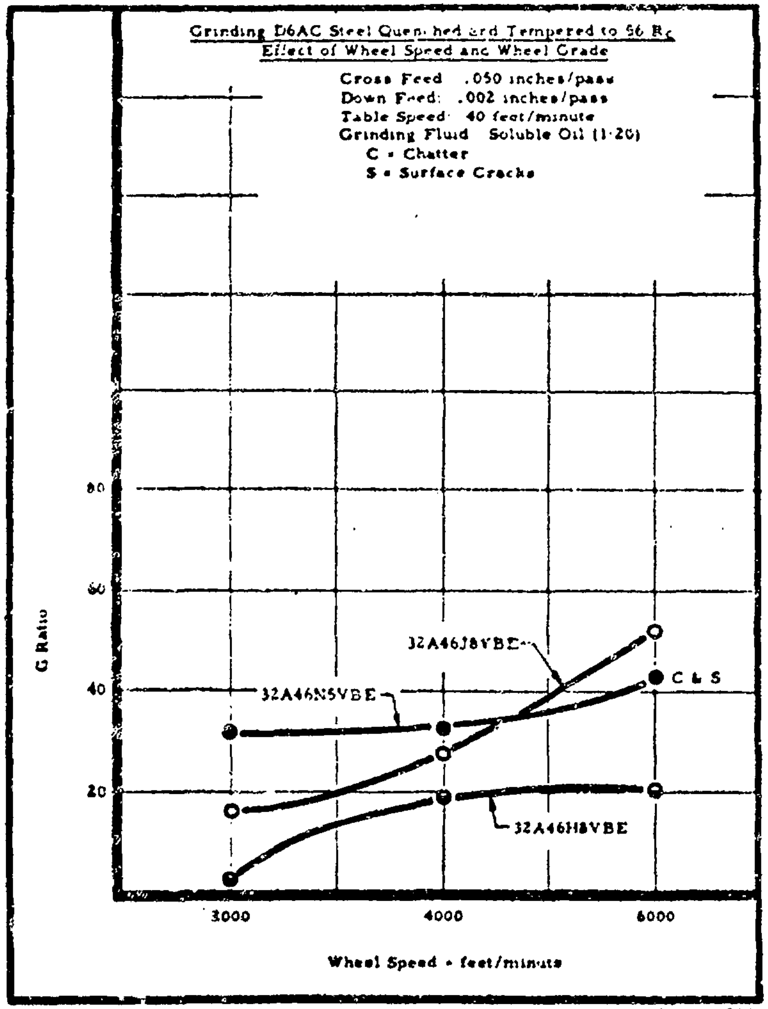

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Figure 280

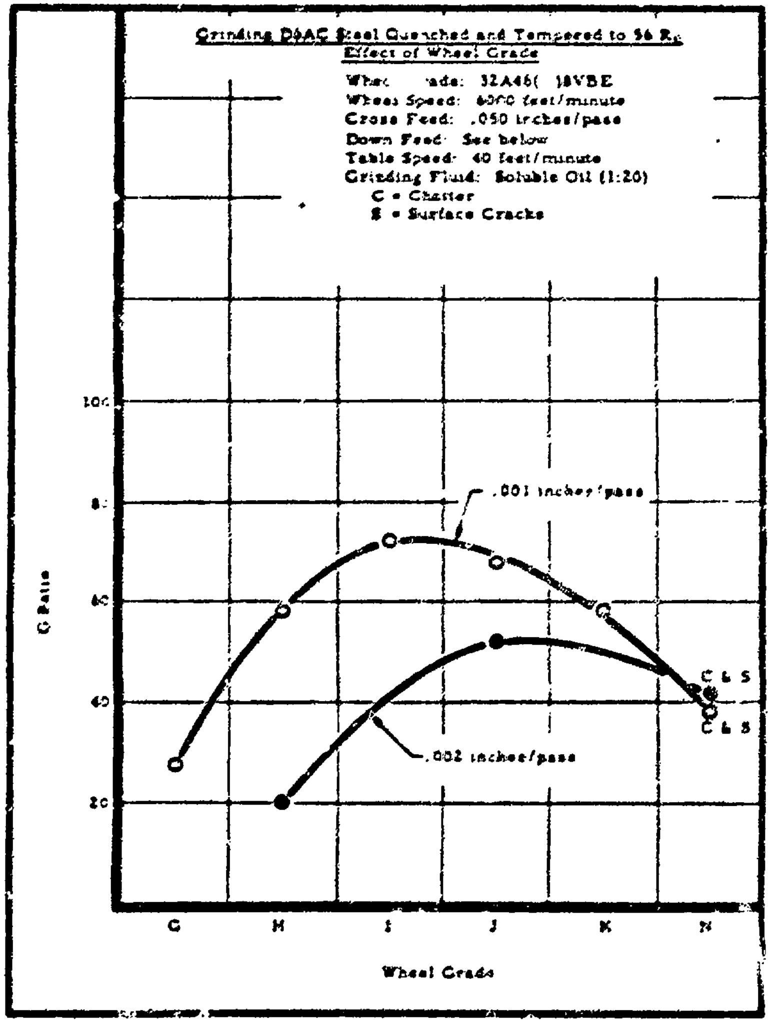

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Figure 281

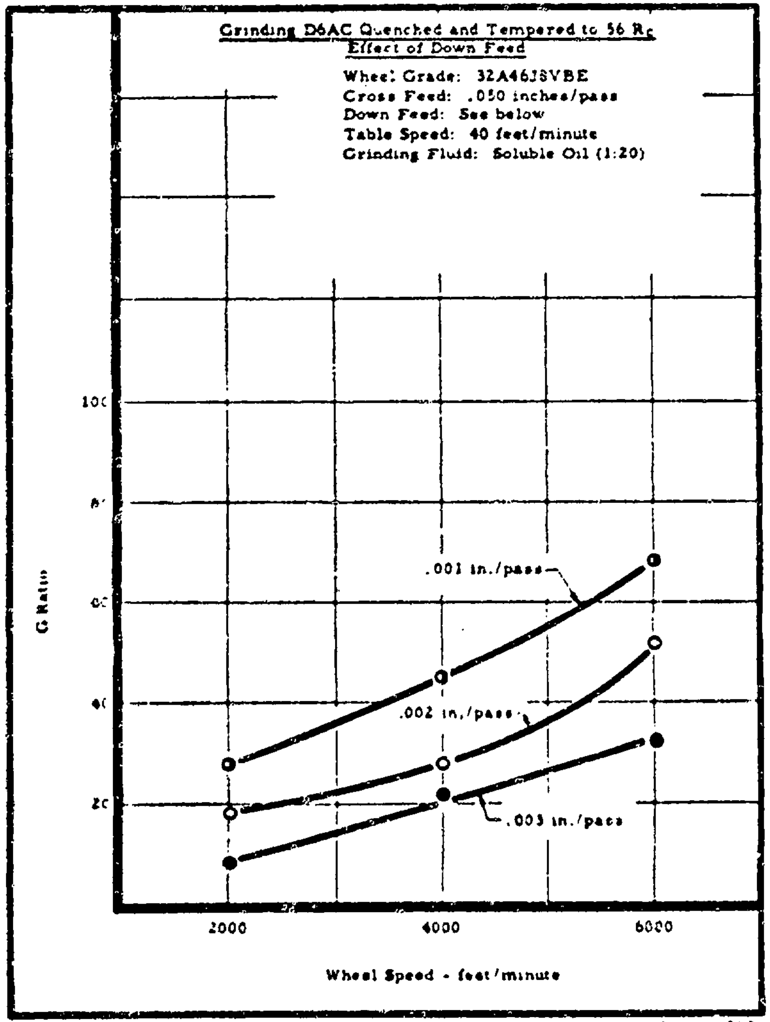

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Figure 282

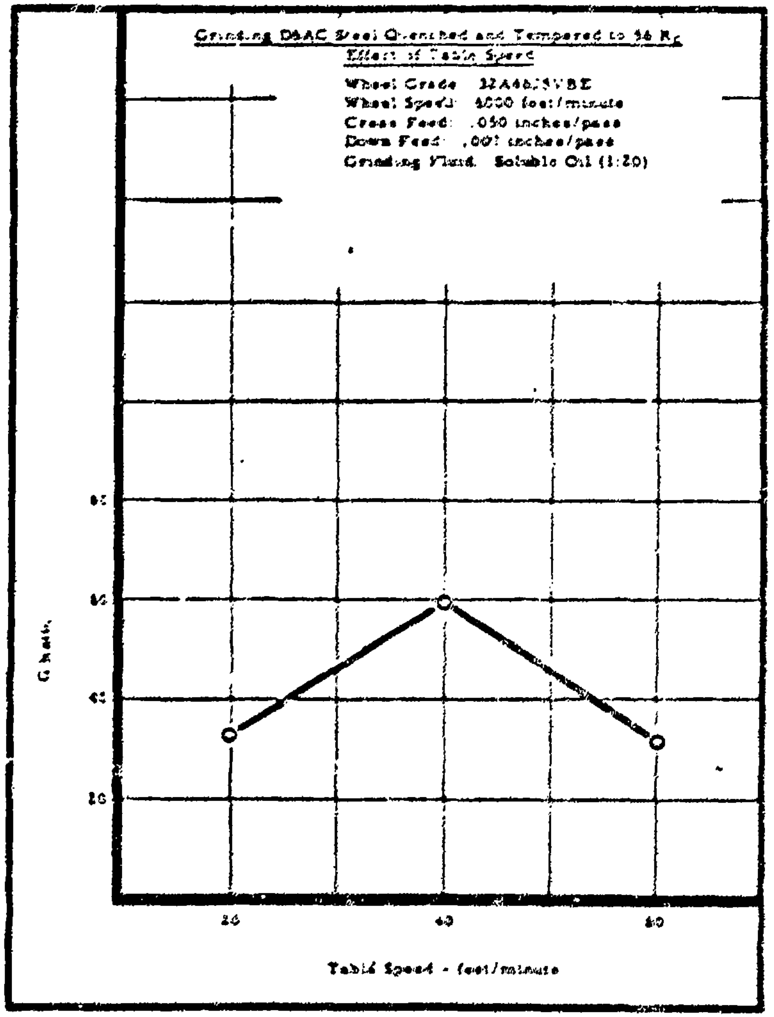

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Figure 283

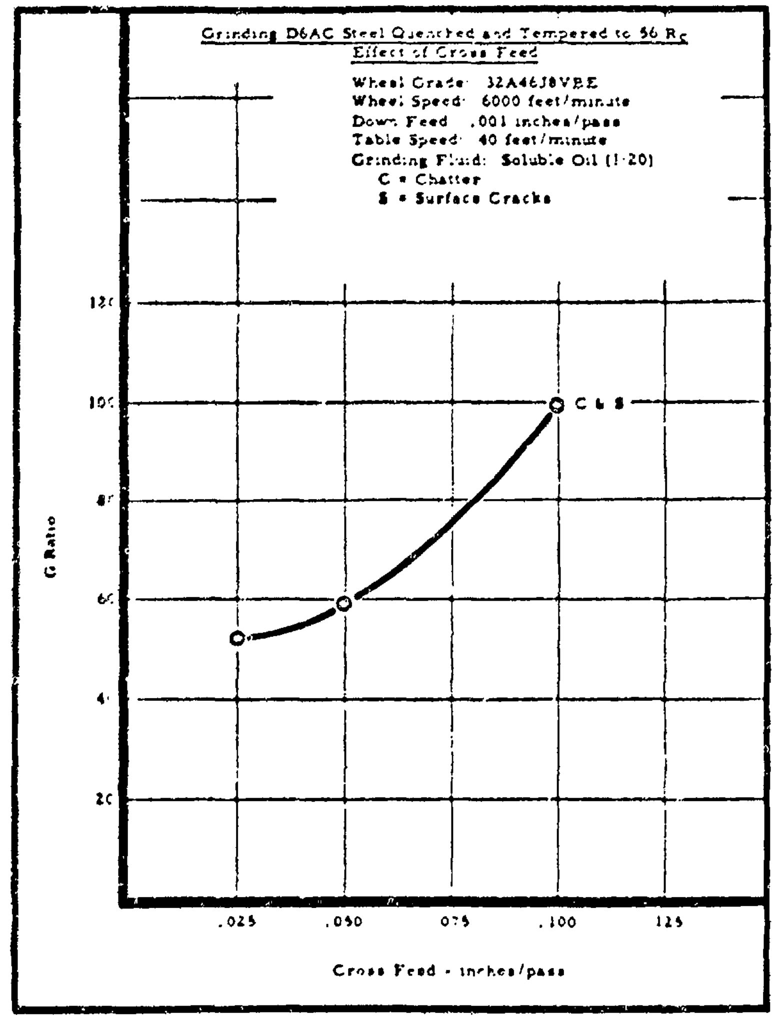

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Figure 284

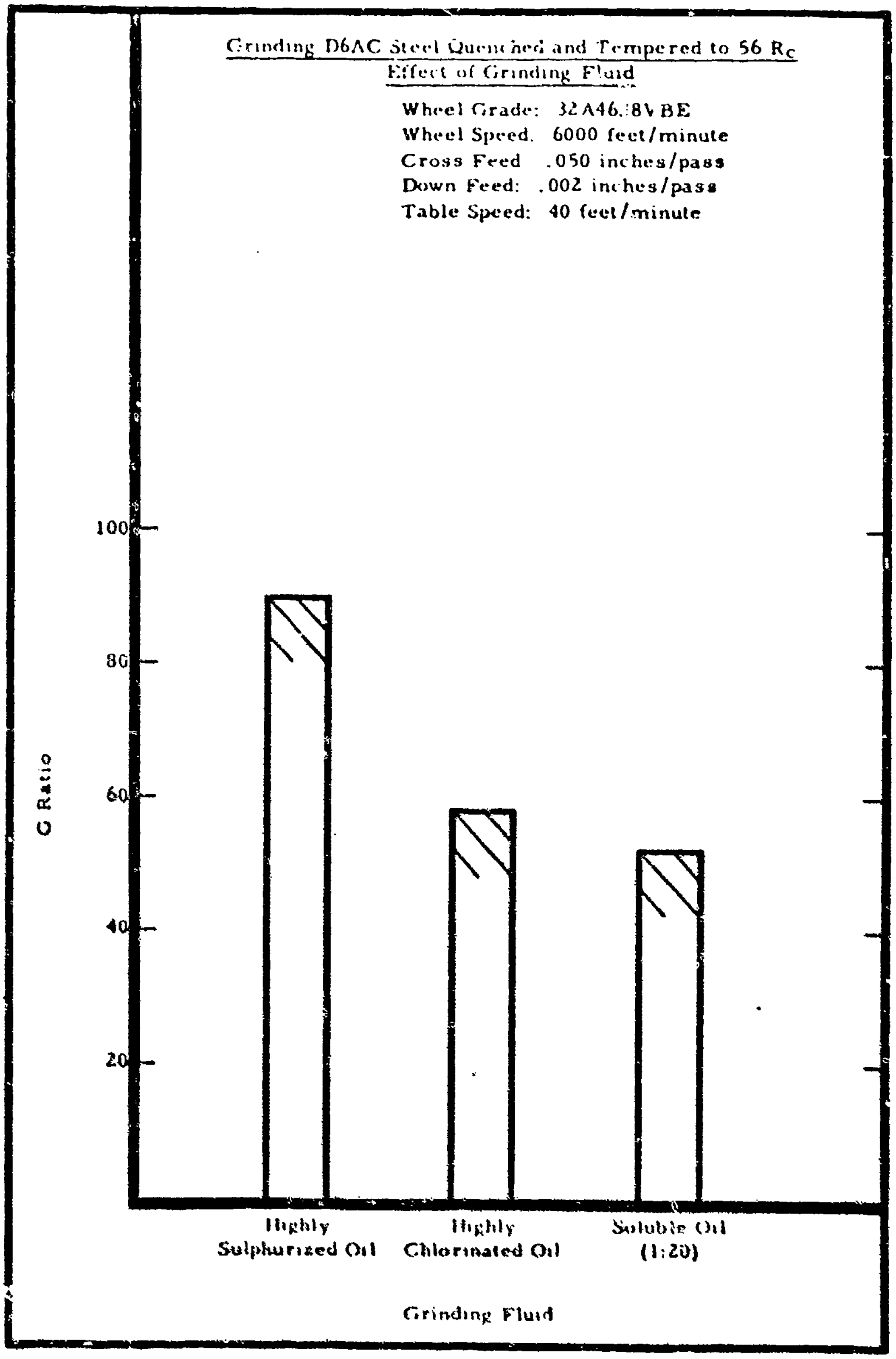

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Figure 285

XI. DISTORTION AND RESIDUAL STRESS STUDIES IN SURFACE GRINDING AND MILLING

Surface grinding and milling tests were made on selected alloys to study the effect of grinding and milling variables on distortion. Test specimens from the distortion studies were used for the residual stress analyses. The stress analyses were made to define the types and magnitude of residual stresses induced by the grinding and milling operations.

Distortion Studies Procedure

The distortion studies were made using test specimens manufactured under carefully controlled conditions. The test specimens were rough machined, then heat treated if necessary. Finish grinding to size was done using a low stress grinding technique. The specimens were 3/4" wide by 4-1/4" long, see Figure 286, page 242. Thickness of the specimens was .070" for grinding and .100" for the milling tests. The sample thickness after test machining was .060" for each specimen.

The test specimens were held in a special fixture, Figure 287, page 243, for the grinding and milling tests. The tapered clamp along the length of the sample provided positive clamping, which permitted uniform stock removal.

The curvature of each specimen was carefully measured before and after test machining. Through this procedure the change in curvature, or workpiece distortion, resulting from the machining process was established for a variety of grinding and milling conditions. Figure 288, page 243, shows the fixture used in measuring curvature, and Figure 289, page 244, shows how the deflection measurements were obtained on this fixture.

Residual Stress Analysis Procedure

Residual stress analyses were made on selected test specimens from the distortion studies to determine the types and magnitude of the stresses induced by grinding or milling.

The procedure used in the stress analysis was one of progressively etching off the test surface in uniform small increments and noting the change in deflection of the specimen. The deflection measurements were made using the same fixture used in the distortion studies, Figure 288, page 243. The depth of stock removed versus change in deflection data was then used to calculate the residual stress at any depth below the surface of the specimen. The calculations were made using an equation developed by Messrs. Thomsen and Frisch* to determine the uniaxial stress in the longitudinal direction of the test specimen.

* Residual Grinding Stresses in Mild Steel - J. Frisch and E. G. Thomsen, ASME Paper No. 50-F-10, 1950.

Distortion in Surface Grinding Tests on Pressed and Sintered Tungsten

Figure 290, page 245, shows the effect of wheel speed and grinding fluid in distortion in grinding pressed and sintered tungsten, 95% density, 34 R_c. With a soluble oil grinding fluid, the distortion increased from less than .001" at wheel speeds of 2000 and 3000 feet/minute to almost .007" when the wheel speed was increased to 4000 feet/minute. With a nitrite solution, however, the distortion decreased from .004" at a wheel speed of 2000 feet/minute to .002" when the wheel speed was increased to 4000 feet/minute. These tests were performed with a 32A46N5VBE wheel, a table speed of 40 feet/minute, a down feed of .001 in./pass and a cross feed of .050 in./pass.

The effect of wheel grade is shown in Figure 291, page 245. This chart shows that the difference did not change appreciably when the wheel hardness was increased from a "J" grade to an "N" grade.

Figure 292, page 246, shows that down feed also has little effect on distortion in grinding pressed and sintered tungsten, 95% density, 34 R_c. With a 32A46N5VBE wheel, operating at 2000 feet/minute using a nitrite grinding fluid, the distortion remained almost constant at .004" over a down feed range of .0005 in./pass to .002 in./pass.

Residual Stress Analysis Tests on Pressed and Sintered Tungsten

Stress analyses were performed on selected specimens from the distortion studies to evaluate the magnitude and type of residual stresses produced by surface grinding pressed and sintered tungsten. The calculated stress at any depth is plotted to show the distribution of the residual stress below the ground surface. The area under the stress distribution curve is a measure of the total induced stress. The greater the area under the curve, the greater the total stress in the surface and, hence, the greater the distortion that is produced.

The results of the stress analysis on the surface ground specimens are given in Figures 293 through 297, pages 246 through 248. The effect of wheel grade is shown in Figure 293, page 246. The stress distribution curves show that a relatively soft "J" grade wheel produced a greater stress than the harder "L" and "N" grade grinding wheels. A maximum stress of 70,000 to 90,000 psi was produced in the test specimens .0005" below the surface. This stress was compressive in nature. At depths beyond .002" below the surface, little or no stress was produced in test specimens.

Figure 294, page 247, shows the effect of wheel speed when surface grinding with a 32A46N5VBE wheel using a nitrite grinding fluid. With a wheel speed of 2000 feet/minute, a maximum compressive stress of 90,000 psi was produced at a depth of about .0004" below the surface. When the wheel speed

was increased to 4000 feet/minute, the maximum compressive stress produced was about 70,000 psi at slightly more than .0005" below the surface. The residual stress distribution seen in this chart checks favorably with the distortion observed in the test specimens discussed previously.

The effect of wheel speed in surface grinding with a 32A46N5VBE wheel using a soluble oil grinding fluid is shown in Figure 295, page 247. The maximum stress was produced when a wheel speed of 4000 feet/minute was used. When the wheel speed was reduced to 2000 feet/minute, the residual stress was also reduced. It is interesting to note that the stress was tensile in nature when a soluble oil grinding fluid was used and compressive when a nitrite grinding fluid was used.

Figure 296, page 248, indicates that a down feed of .002 in./pass produced a lower residual stress than down feeds of .001 and .0005 in./pass. These tests were run using a 32A46N5VBE wheel operating at 2000 feet/minute with a nitrite grinding solution. The stresses are all compressive in nature, which is consistent with the data shown previously.

The effect of grinding fluid is shown in Figure 297, page 248, on the residual stress produced in pressed and sintered tungsten. This chart shows that approximately the same stress distribution is produced in the workpiece when a highly sulphurized grinding oil and a nitrite grinding solution is used. Both grinding fluids produce compressive stresses of about 90,000 psi in the specimens .0005" below the surface. When a soluble oil is used in grinding, the stress produced is tensile in nature and reaches a peak of about 30,000 psi right at the surface of the specimen.

Residual Stress Analysis Tests on TZM Molybdenum Alloy

The data presented in Figures 298 through 301, pages 249 and 250, show the effects of wheel grade, grinding fluid, down feed, and wheel speed on the residual stress induced in TZM molybdenum during surface grinding.

Figure 298, page 249, shows that when using three different wheel hardnesses, the softest wheel tested, a "J" hardness wheel, produced a maximum compressive stress of about 38,000 psi at about .0005" below the surface. When an "N" hardness wheel was used, a maximum compressive stress of 30,000 psi was produced, while an "L" hardness wheel produced a compressive stress of about 25,000 psi. These stresses decreased to about zero at a depth of .002" below the surface.

When surface grinding TZM molybdenum with an "L" hardness wheel operating at 4000 feet/minute using a highly sulphurized oil or a water base soluble oil, a

tensile stress of 20,000 psi was produced at a depth of .0015 to .002" below the surface. See Figure 299, page 249. However, when a 5% KNO_2 solution was used, a maximum compressive stress of 25,000 psi was produced at about .0007" below the surface.

The effect of down feed on the residual stress produced in this alloy in surface grinding is shown in Figure 300, page 250. A down feed of .002 in./pass produced a maximum compressive stress of almost 40,000 psi at a depth of .0005" below the surface. When a down feed of .001 in./pass was used, the maximum stress was reduced to about 25,000 psi. However, at a very light down feed of .0005 in./pass, the maximum compressive stress increased to about 32,000 psi.

In determining the effect of wheel speed, Figure 301, page 250, shows that a high wheel speed of 6000 feet/minute produced a maximum tensile stress of 40,000 psi at the surface of the test specimen. This stress decreased very rapidly to zero, then went compressive in nature to a stress of about 26,000 psi at about .0005" below the surface. Wheel speeds of 2000 and 4000 feet/minute produced essentially the same stress pattern, a maximum compressive stress of about 22,000 psi at about .0005" below the surface.

Distortion in Surface Grinding Rene 41

Figure 302, page 251, shows the distortion produced in surface grinding Rene 41 solution treated and aged to 365 BHN using different wheel speeds, wheel grades and down feeds. With an "H" hardness wheel, distortion increased from .002 to .004" when the wheel speed was increased from 2000 to 6000 feet/minute. With a harder "L" grade wheel, the distortions increased from .002" in compression to .021" in tension when the wheel speed was increased from 2000 to 6000 feet/minute.

The down feed per pass used in surface grinding Rene 41 also affects distortion significantly. With a "J" hardness wheel operating at 4000 feet/minute, a distortion of about .019" was produced in the workpiece when a .002 in./pass down feed was used.

The effect of grinding fluids on distortion is presented in Figure 303, page 251. With a "J" hardness wheel at 4000 feet/minute, a distortion of .014 to .016" was produced in the workpiece when a water base soluble oil emulsion and chemical solution were used. A highly sulphurized oil, however, reduced the distortion to about .002" when a down feed of .001 in./pass was used and about .001" when a "low stress" down feed was used. The "low stress" down feed consisted of removing the last .002" by progressively reducing the down feed per pass from .001 in./pass to .0002 in./pass.

Residual Stress Analysis Tests on Rene 41

The results of the stress analysis on the ground surface of the Rene 41 specimen are shown in Figures 304 through 308, pages 252 through 254. The effect of wheel hardness when surface grinding with a wheel speed of 6000 feet/minute, presented in Figure 304, page 252, shows that the stress pattern and magnitude are very nearly the same for a medium "J" hardness wheel and a relatively hard "L" wheel. This chart shows that at high wheel speeds, the hardness of the wheel has little effect on the stress.

Figure 305, page 252, shows the stress distribution obtained when grinding this alloy with "H" and "J" hardness wheels using a wheel speed of 4000 feet per minute and a low stress down feed procedure. The "H" hardness provided a maximum compressive stress of 85,000 psi a few tenths below the ground surface. A maximum compressive stress of 40,000 psi was produced at the surface of the specimen ground with the "J" hardness wheel. However, at .002 to .004" below the surface, the "J" hardness wheel produced a higher tensile stress than the "H" hardness wheel.

The effect of wheel speed when using a "J" hardness wheel with a .001 in./pass down feed is shown in Figure 306, page 253. This chart shows that a relatively high compressive stress is produced immediately below the ground surface when a wheel speed of 2000 feet/minute was used. With a wheel speed of 6000 feet/minute, a tensile stress exceeding 80,000 psi was produced. At an intermediate wheel speed of 4000 feet/minute, a compressive stress was produced just below the surface which changed to a tensile stress at about .002" below the surface.

Two wheel speeds, 2000 feet/minute and 4000 feet/minute, were evaluated with an "H" hardness wheel using a "low stress" down feed. The data presented in Figure 307, page 253, shows that a maximum compressive stress of 85,000 psi was produced in the workpiece when the 4000 feet/minute wheel speed was used. The stress level was almost zero at about .002" below the surface.

The effect of down feed on the residual stress produced in Rene 41 is shown in Figure 308, page 254. With a "J" hardness wheel operating at 4000 feet per minute using a low stress down feed, a stress of 40,000 psi was produced. A .001 in./pass down feed produced a maximum compressive stress of about 60,000 psi .001" below the surface. When a .002 in./pass down feed was used, a compressive stress of about 40,000 psi was produced just below the surface and a tensile stress of about 50,000 psi at about .003" below the surface.

Distortion in Surface Grinding and Face Milling D6AC Steel Quenched and Tempered 56 R_c

The results of workpiece distortion studies in surface grinding and face milling are shown in Figures 309 through 312, pages 254 through 256.

Figure 309, page 254, shows the effect of wheel grade and wheel speed on distortion for surface grinding D6AC steel quenched and tempered to 56 R_c. The soft grade 32A46H8VBE wheel produced a very low distortion of about .001" at wheel speeds of 2000 and 4000 feet/minute. Distortion increased to a moderate value of .012" as the wheel speed was increased to 6000 feet/minute. The medium hardness 32A46K8VBE wheel and the harder 32A46N5VBE wheel both produced substantially higher distortions than did the "H" hardness wheel at all three wheel speeds. Distortion increased rapidly with increasing wheel speed for the two harder grade wheels. At a wheel speed of 2000 feet/minute, .010" distortion was produced by the "K" wheel and .022" by the "N" wheel. Distortion increased to .035" for the "K" wheel and .058" for the "N" wheel at a wheel speed of 6000 feet/minute.

The effect of down feed on distortion is shown in Figure 310, page 255. A 32A46K8VBE wheel with soluble oil as the grinding fluid was used for these tests. Using a "low stress" down feed procedure, only negligible distortion was produced for wheel speeds between 2000 and 6000 feet/minute. For a down feed of .001 in./pass, distortion increased from .003" at 2000 feet/minute wheel speed to .020" at 6000 feet/minute. The distortion produced by a down feed of .002 in./pass was appreciably more than double that for a .001 in./pass down feed. This data clearly points out the advantage of using very light down feeds, particularly at conventional wheel speeds of 5000 to 6000 feet/minute when distortion of the workpiece is an important consideration.

The effects of grinding fluid and wheel speed on distortion are shown in Figure 311, page 255. Very low distortion was produced at wheel speeds of 2000 and 4000 feet/minute when using a highly sulphurized oil, as compared to distortion obtained when using a soluble oil at the same wheel speeds. However, at 6000 feet/minute, distortion with sulphurized oil as the grinding fluid was equal to the .035" produced with soluble oil.

Results of distortion studies for face milling 56 R_c D6AC steel are shown in Figure 312, page 256. The effect of tool wear and depth of cut are indicated. For a .010" and a .040" depth of cut, distortion increased rapidly as the tool wearland increased from .000" (sharp tool) to .016". Using a sharp tool, a deflection of .015" was obtained for both the .010" and the .040" depth of cuts. Maximum distortion for a .010" depth of cut was .046", compared to .080" for a .040" depth of cut for an identical tool wearland of .016".

Residual Stress Analysis

Stress analyses were performed on selected specimens from the distortion studies, to evaluate the magnitude and type of residual stresses produced by surface grinding and milling the D6AC steel hardened to 56 R_c. The calculated stress on any depth is plotted to show the distribution of residual stresses below the ground or milled surface. The area under the stress distribution curve is a measure of the total induced stress. The greater the area under the curve, the greater the total stress in the surface and, hence, the greater the distortion that is produced.

The stress analyses on surface ground specimens are given in Figures 313 through 318, pages 256 through 259. The effect of wheel grade is shown in Figure 313, page 256. The stress distribution curves show that as wheel hardness is increased the residual stress is increased when surface grinding at 6000 feet/minute with a down feed of .002 in./pass, using a soluble oil grinding fluid. The residual stresses produced by grinding under the above conditions for each wheel tested were primarily tensile type stresses.

Figure 314, page 257, shows the effect of wheel speed on residual stress when surface grinding with a 32A46H8VBE wheel. At the low wheel speed of 2000 feet/minute, fairly low compressive stresses were obtained; while at the high wheel speed of 6000 feet/minute, a higher magnitude of tensile residual stresses were produced in the surface.

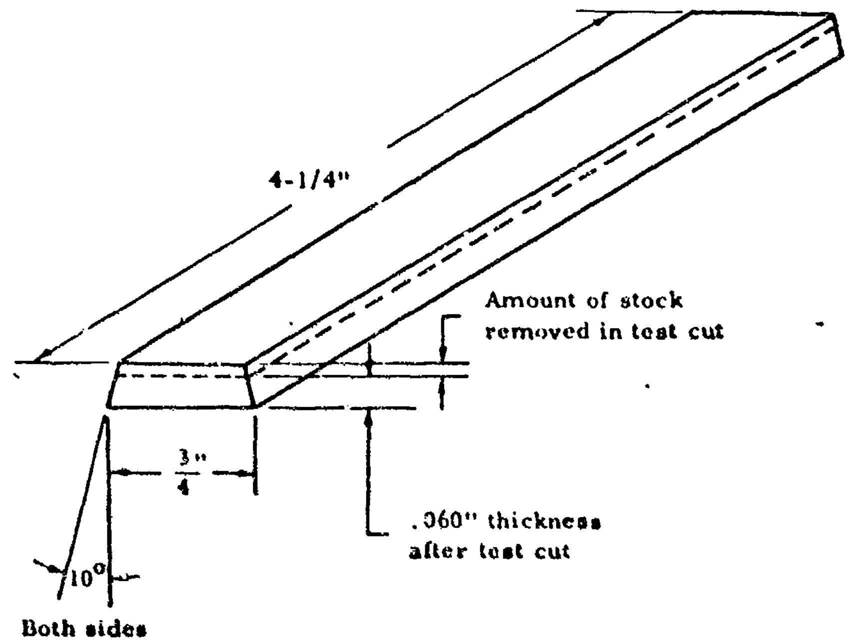
Heavy down feeds produce the greatest residual stress in surface grinding the hardened D6AC steel, Figure 315, page 257. The greatest residual stress was observed when using a down feed of .002 in./pass, while the least amount of stress was noted when a "low stress" down feed progression was used. With the .001 and .002 in./pass down feeds, tensile residual stresses were produced. Using the "low stress" down feeds, however, a slight compressive stress was produced in the surface.

Figure 316, page 258, shows the effect of grinding fluid in surface grinding of D6AC steel at 56 R_c with a 32A46K8VBE wheel at 6000 feet/minute, a down feed of .002 in./pass and soluble oil and highly sulphurized oil grinding fluids. The stress distribution curves for both the soluble oil and the highly sulphurized oil are about the same, indicating that the residual stress in each case was approximately the same. It should be pointed out that the distortion produced, as measured by deflection measurements, was .035" with the soluble oil and .036" with the highly sulphurized oil (see Figure 311, page 255). The residual stress analysis thus supports the information obtained from the distortion study.

Grinding conditions which produce compressive stresses on the hardened D6AC steel are shown in Figure 317, page 258. With a "K" hardness wheel, a compressive stress was noted when using a high wheel speed, 6000 feet/minute,

and a "low stress" down feed progression. With an "H" hardness wheel, a compressive residual stress was obtained with a heavy down feed, .002 inches per pass and a low wheel speed of 2000 feet/minute.

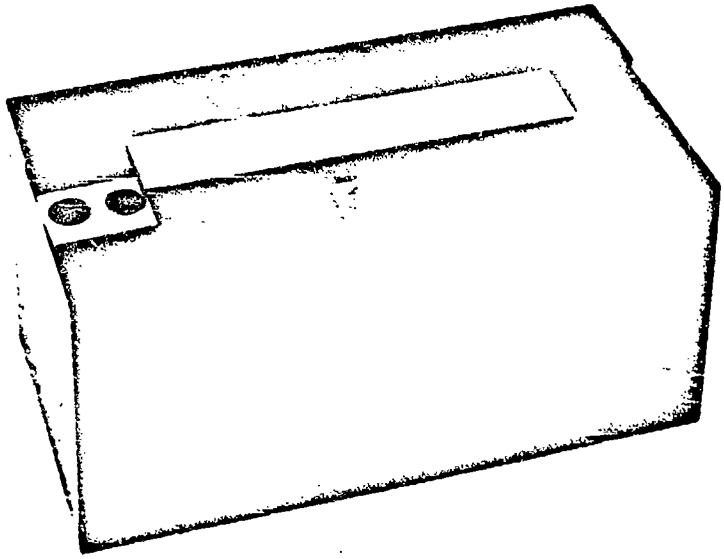
The results of the stress analysis on milled specimens are shown in Figure 318, page 259. The stresses produced in milling were primarily compressive in nature. The stress distribution curves show that as the size of the wearland was increased, the residual stress in the surface of the milled specimen was increased.



DISTORTION AND RESIDUAL STRESS TEST SPECIMEN

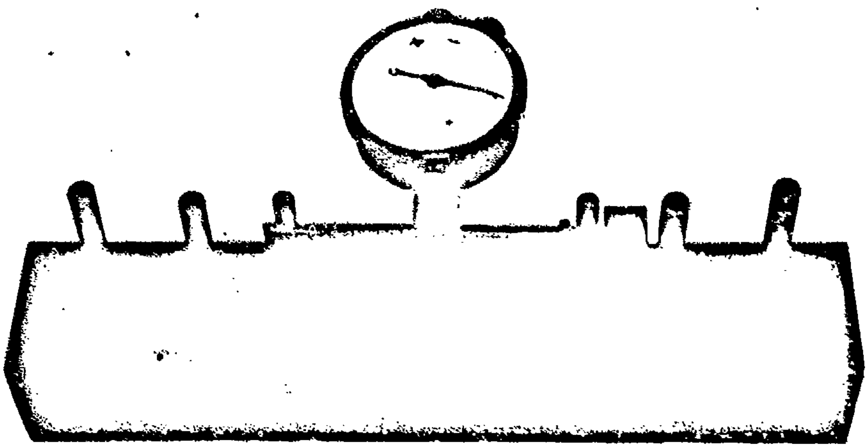
See Text, page 234

Figure 286



Distortion Specimen Holding Fixture

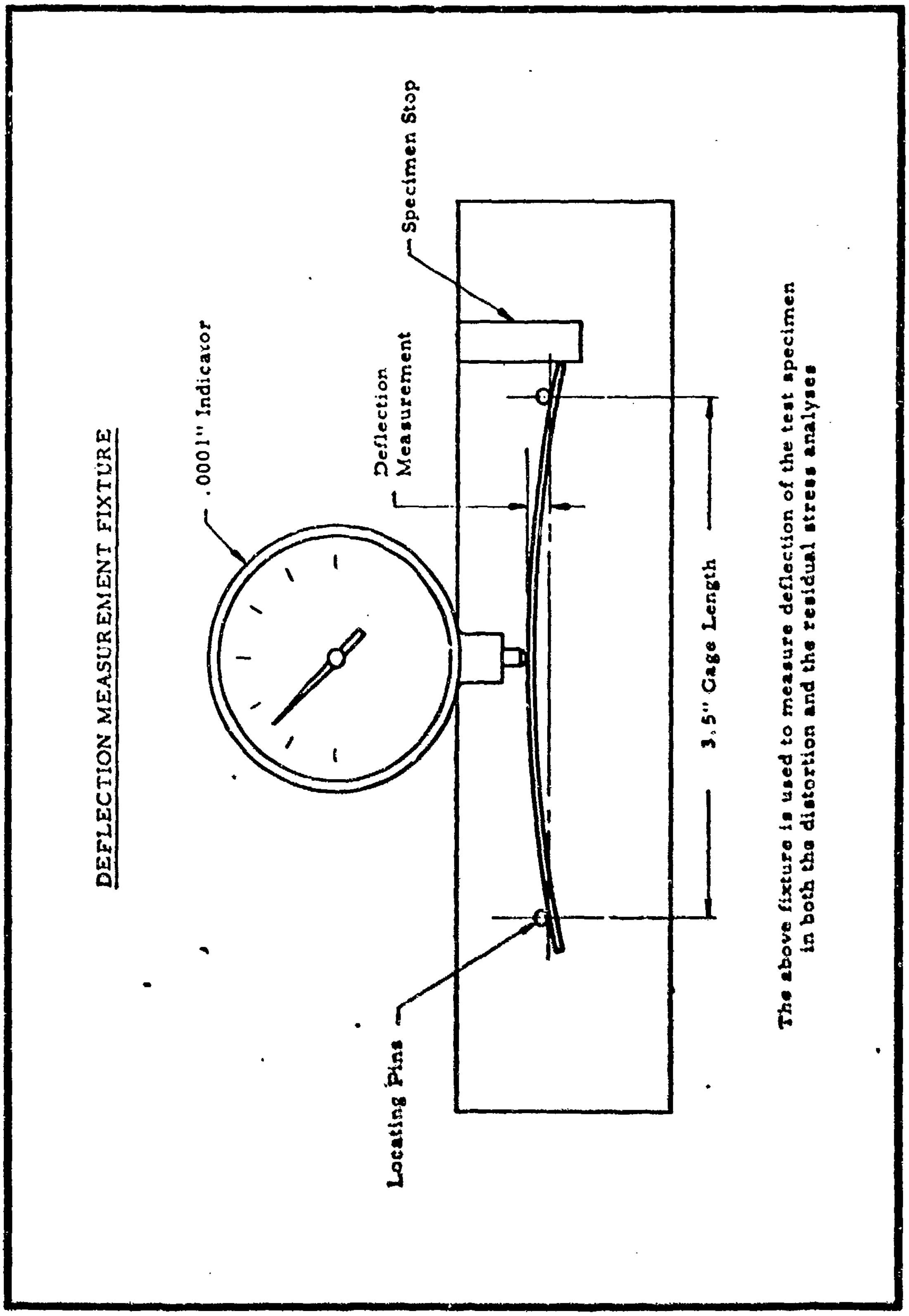
See Text, page 234 Figure 287



Fixture for Measuring Deflection of Distortion Test Specimen

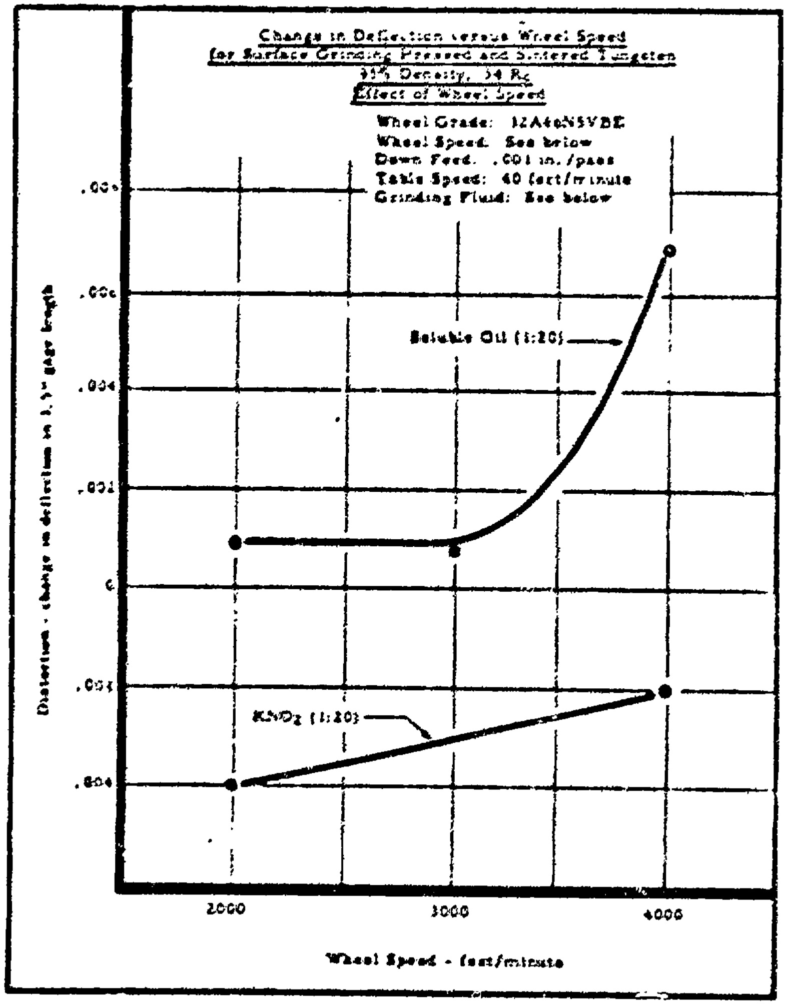
See Text, page 234 Figure 288

DEFLECTION MEASUREMENT FIXTURE



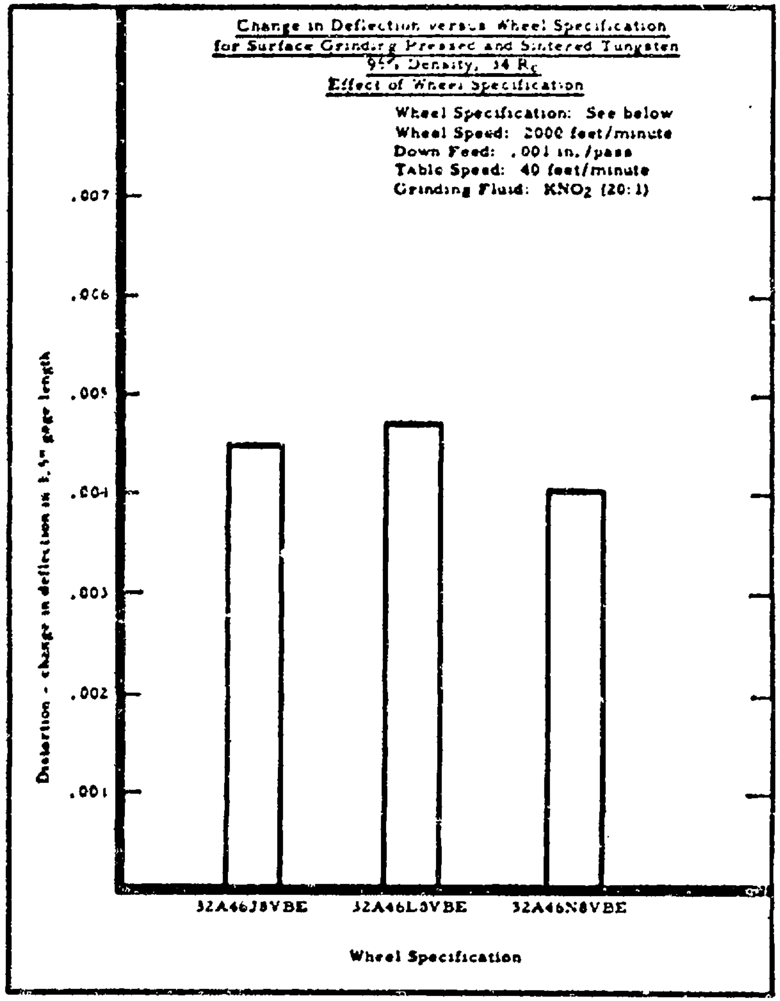
The above fixture is used to measure deflection of the test specimen in both the distortion and the residual stress analyses

See Text, page 234



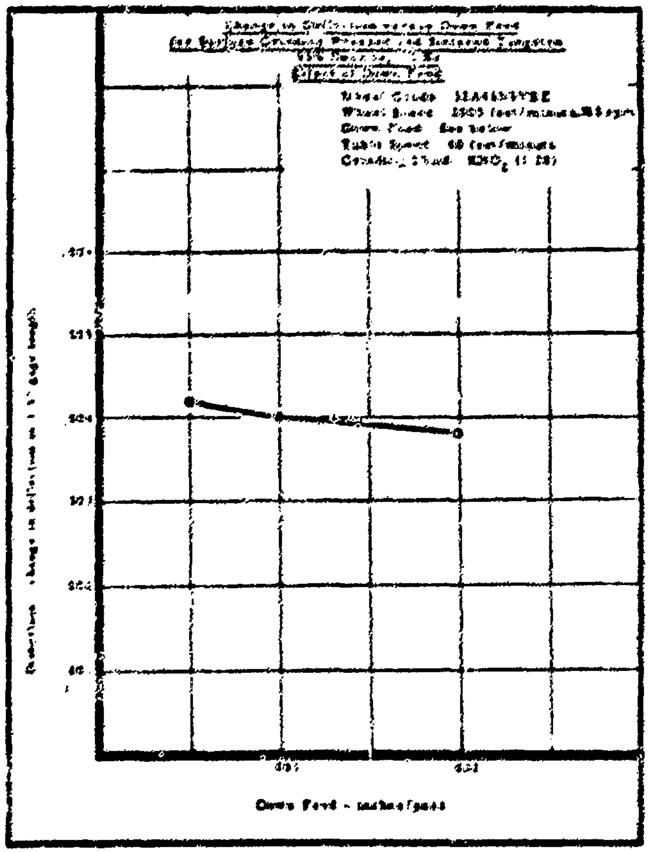
See Text, page 235

Figure 290



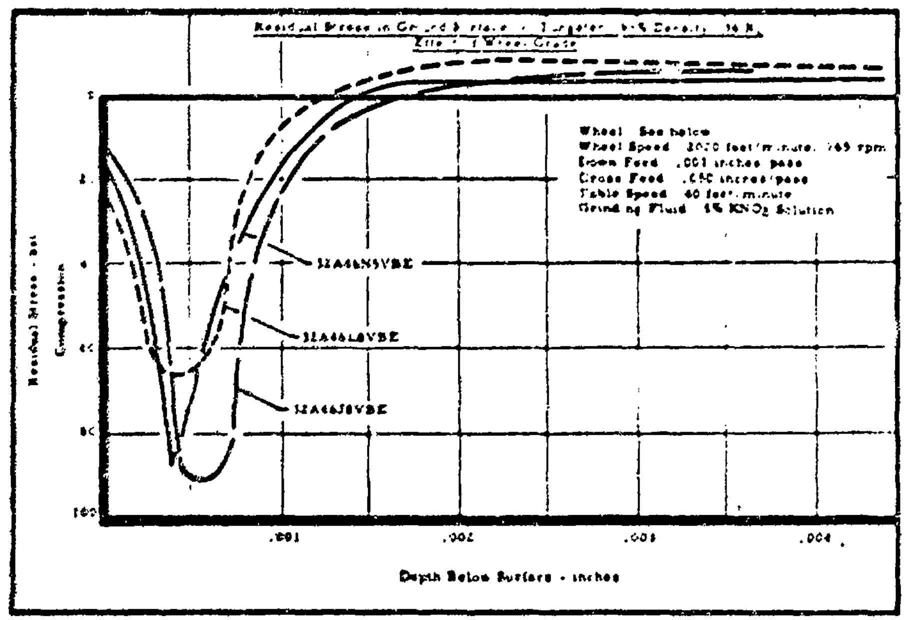
See Text, page 235

Figure 291



See Text page 235

Figure 242



See Text, page 235

Figure 243

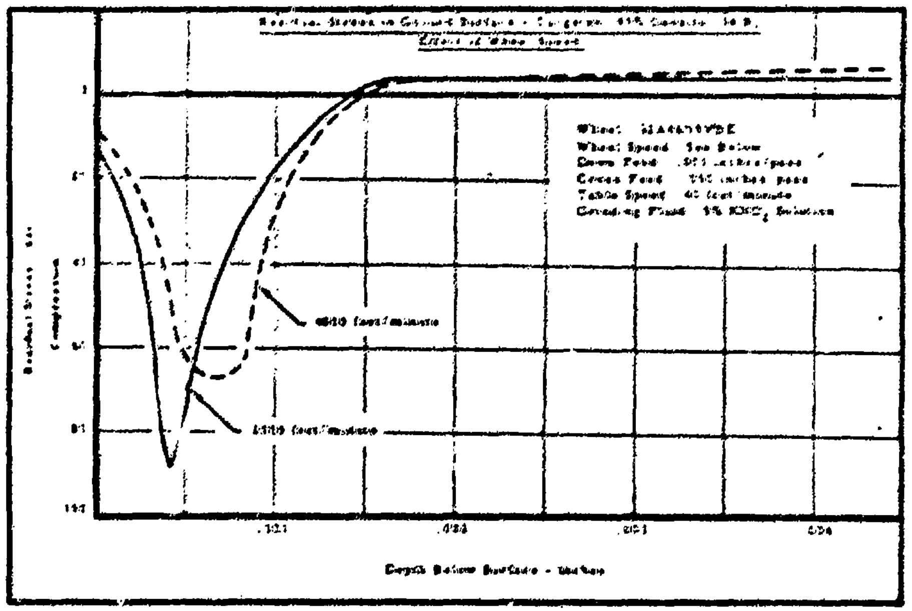


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Figure [illegible]

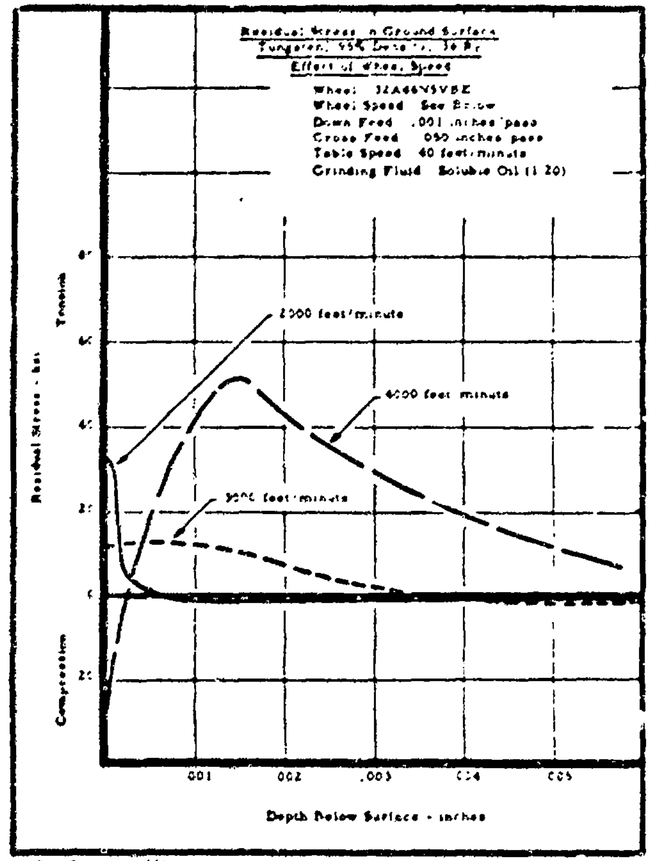

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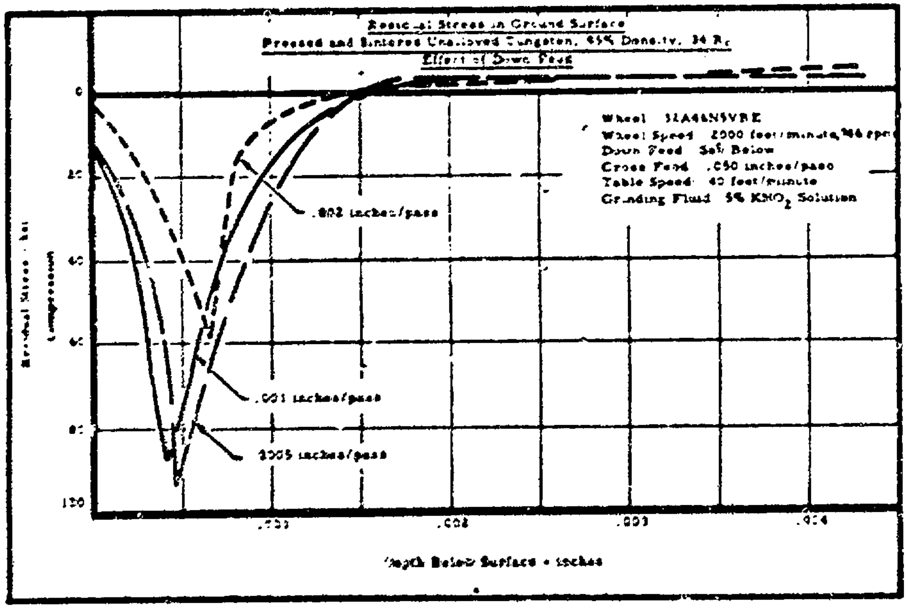
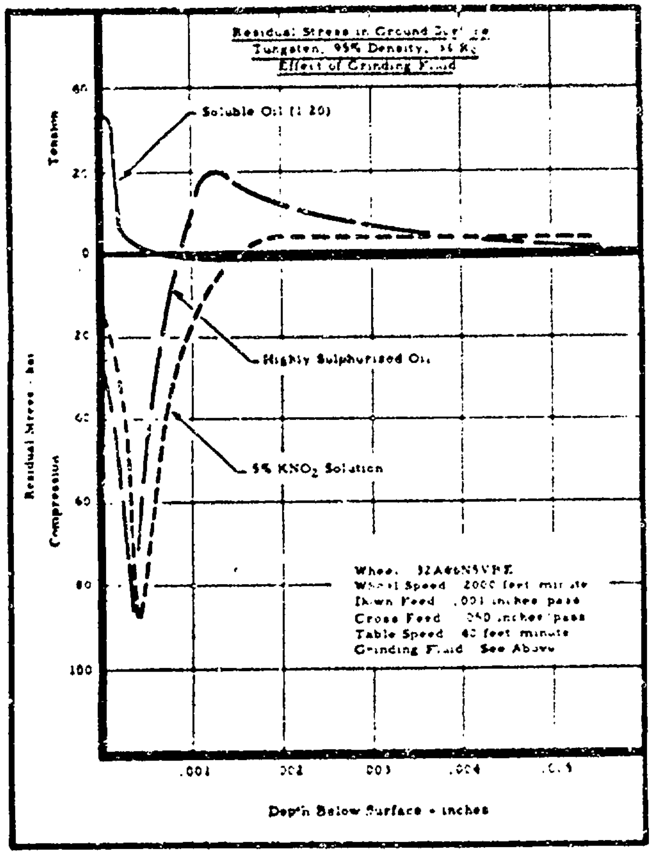
Figure [illegible]



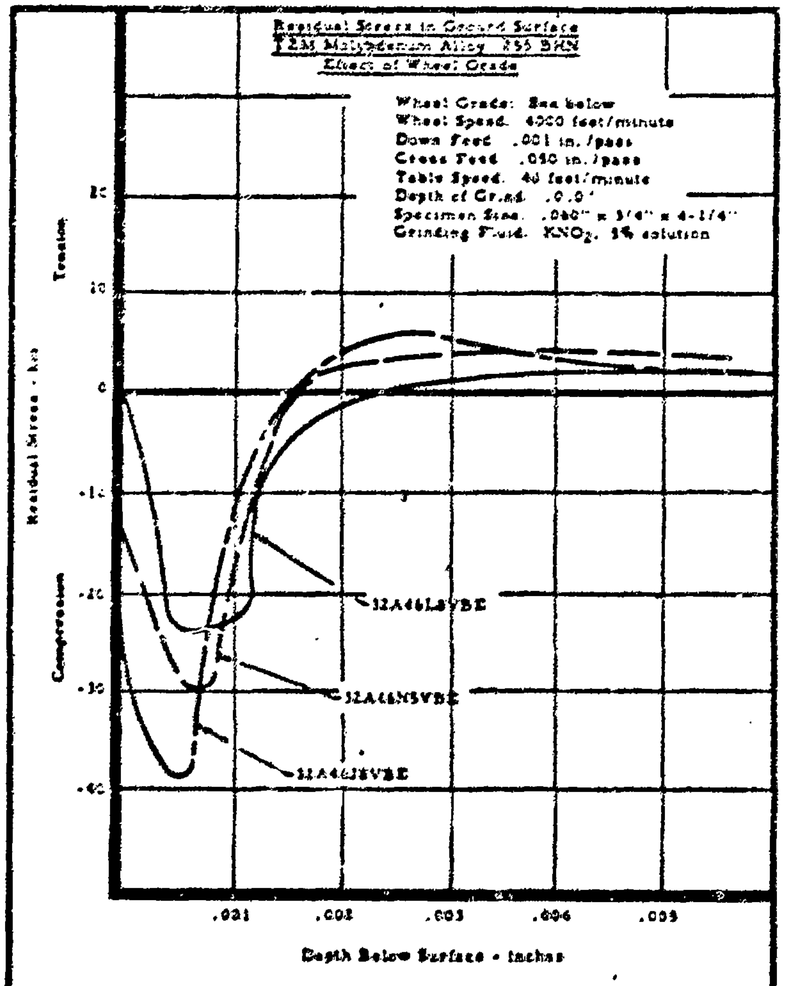
See Text, page 236

Figure 236



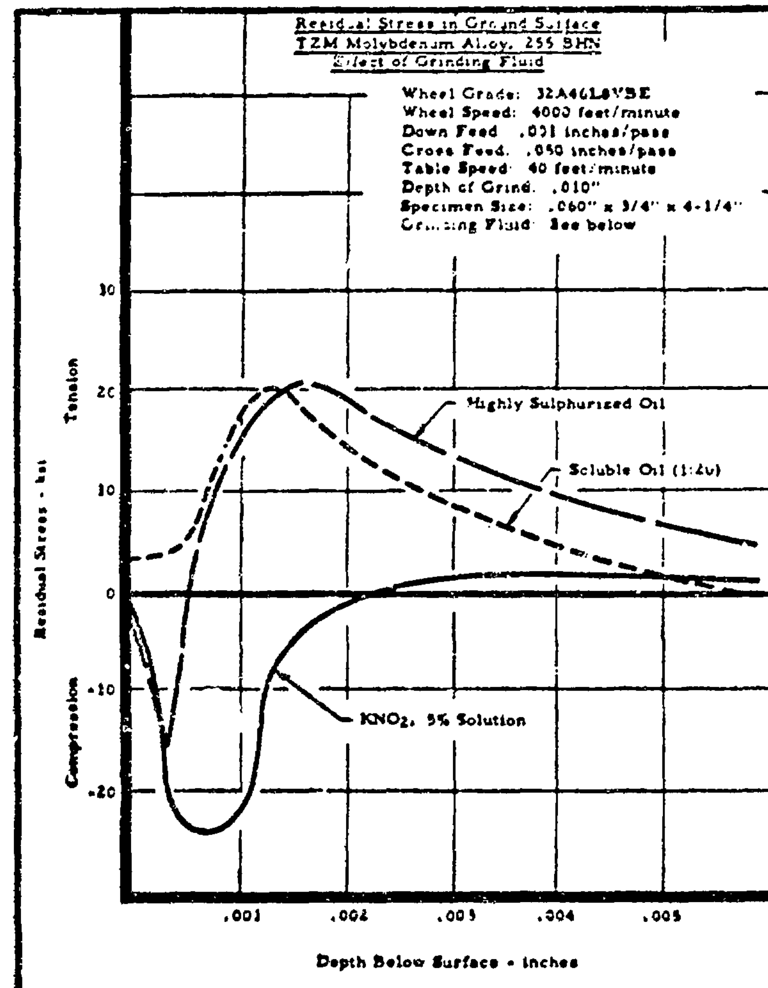
See Text page 236

Figure 237



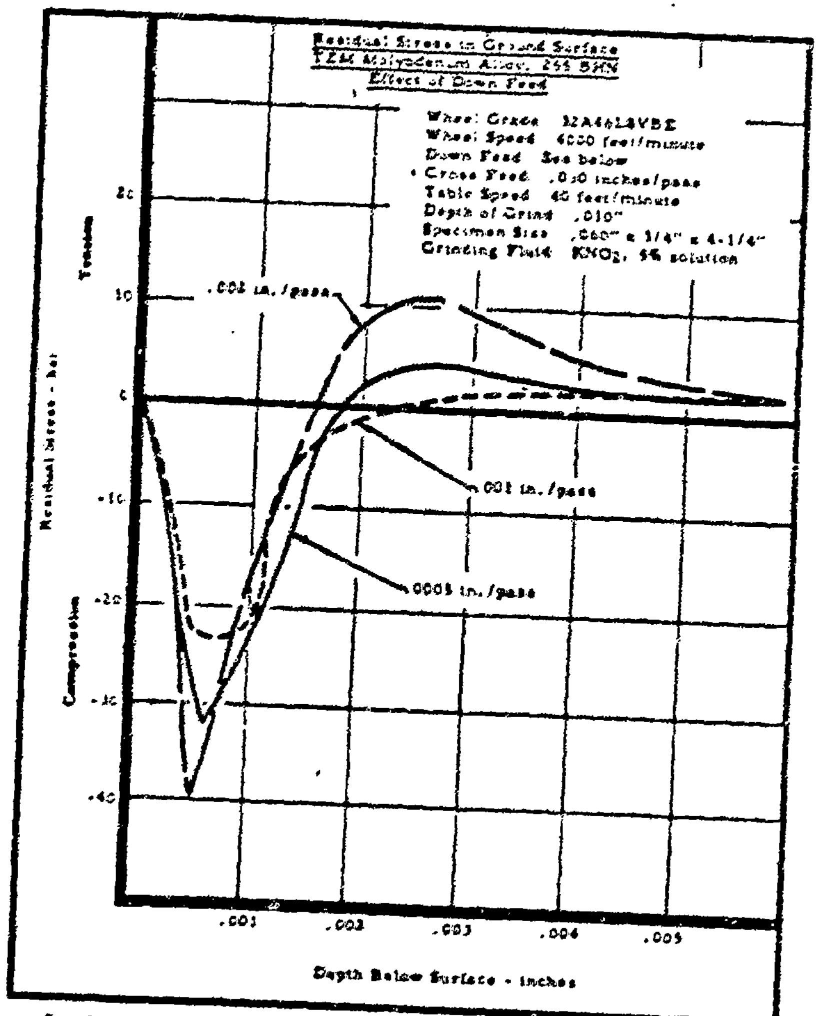
See Text, page 235

Figure 298



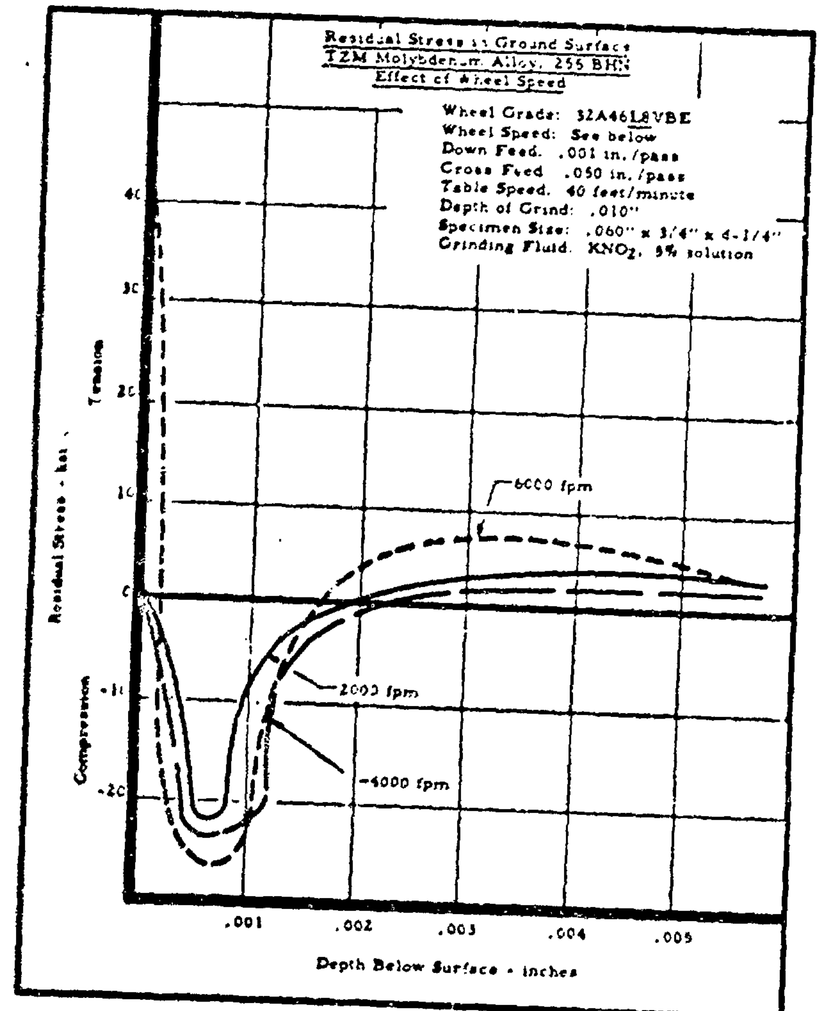
See Text, page 236

Figure 299



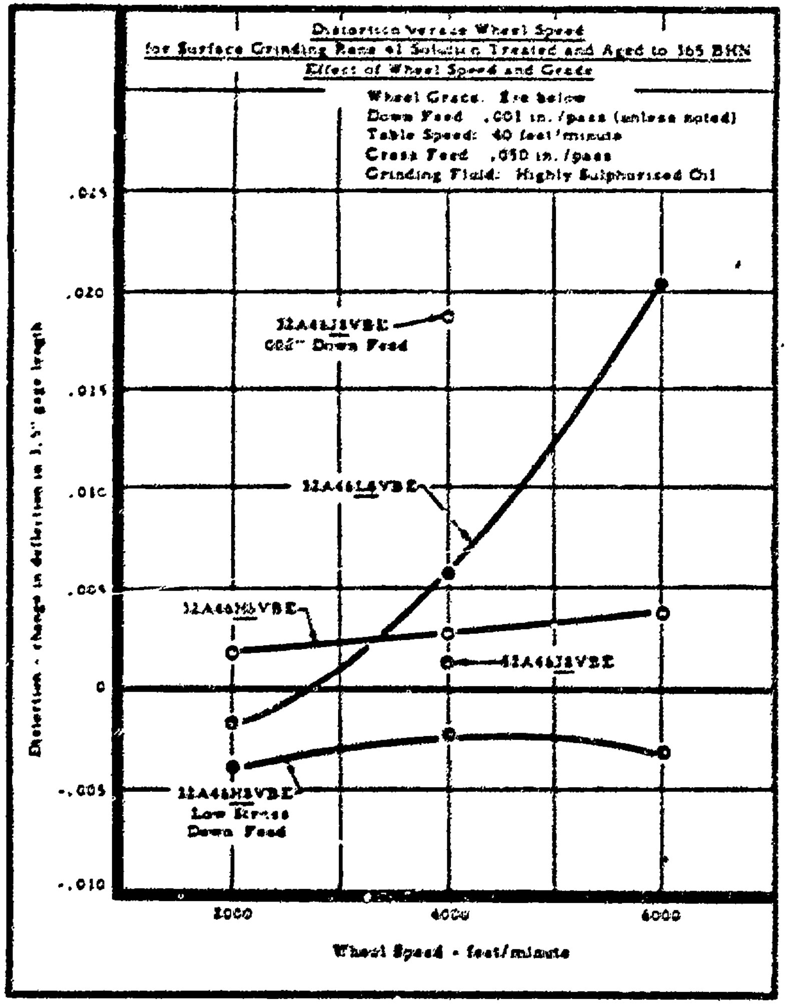
See Text, page 237

Figure 300



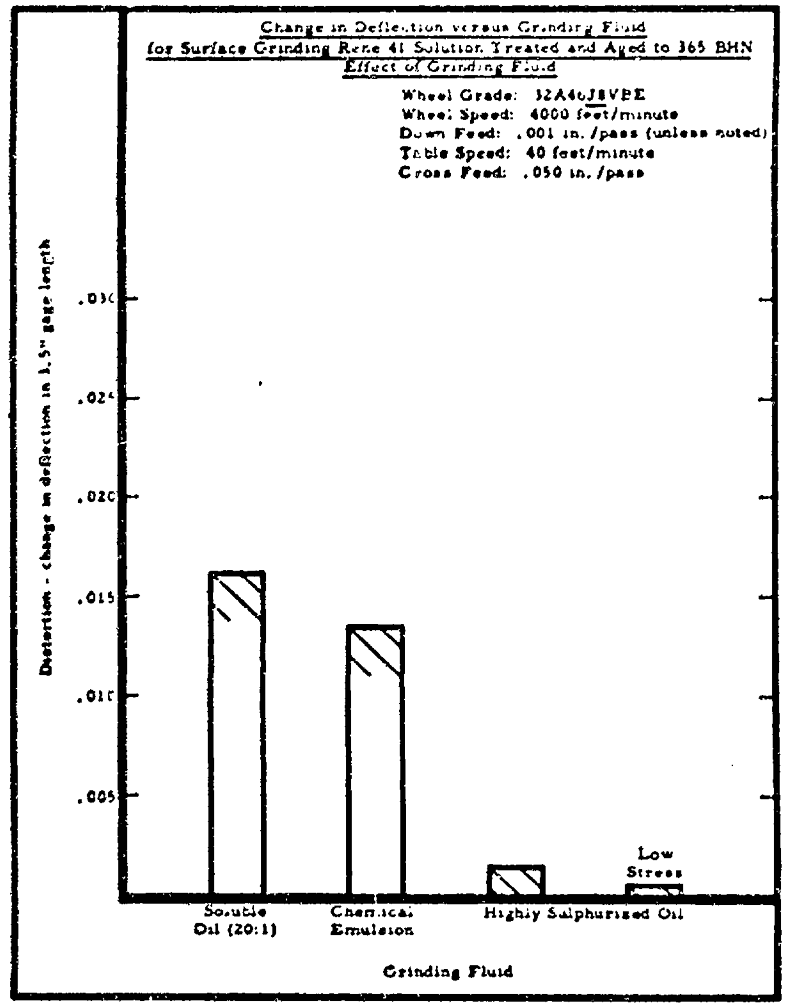
See Text, page 237

Figure 301



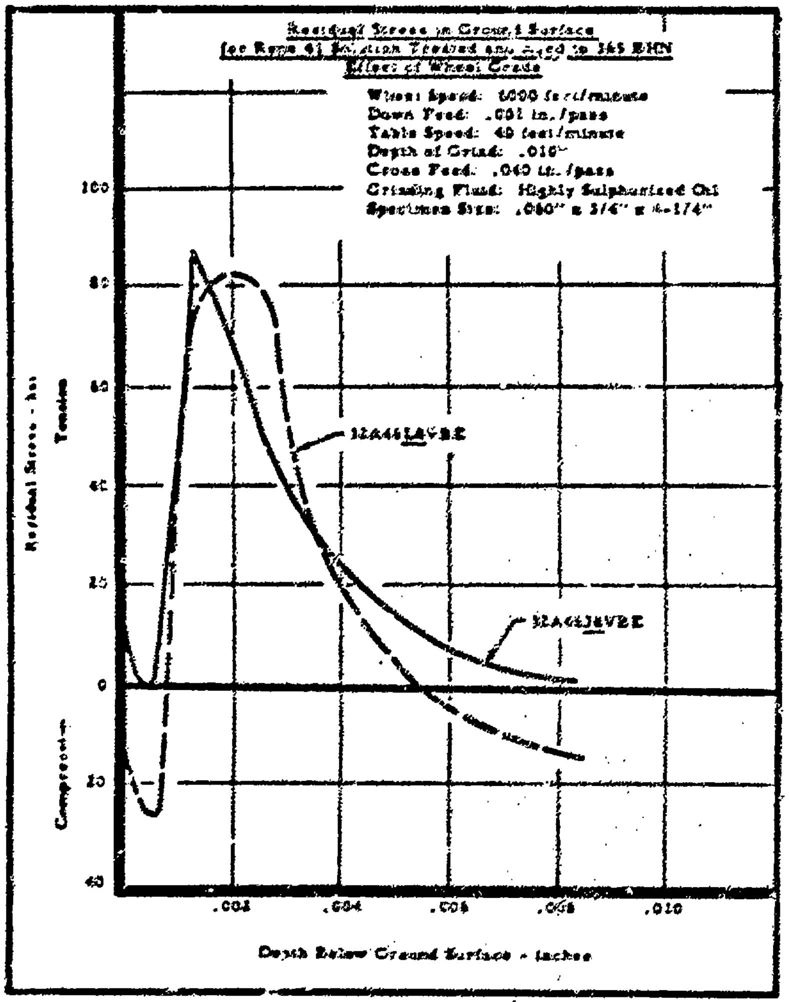
See Text, page 237

Figure 102



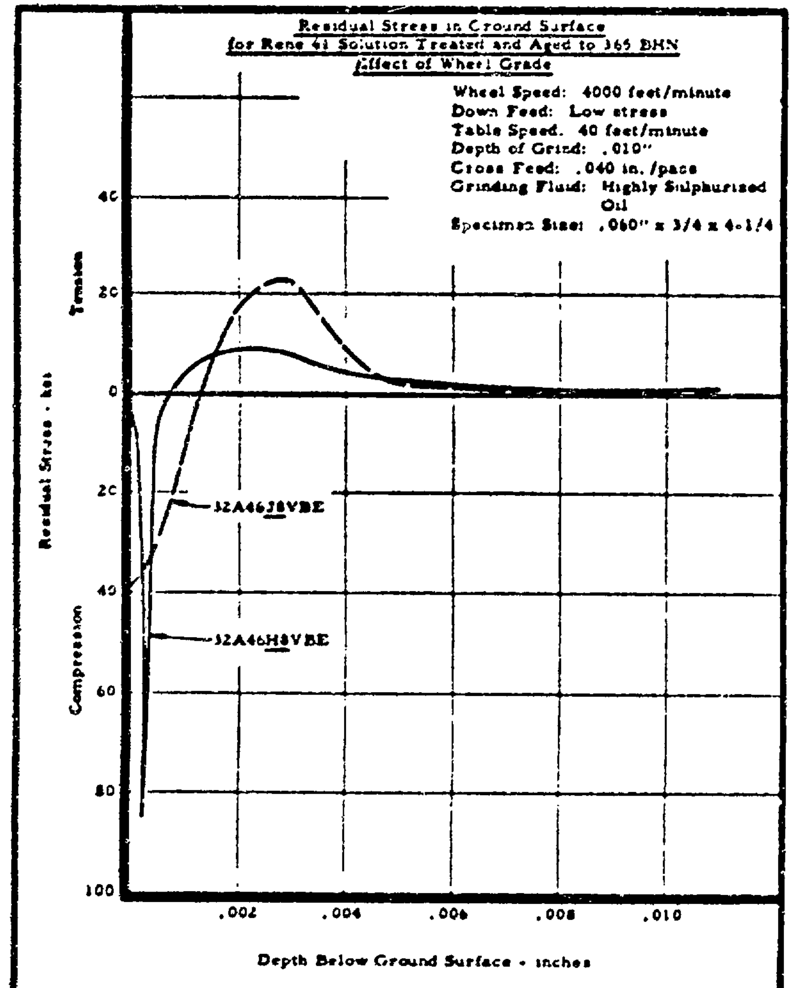
See Text, page 237

Figure 103

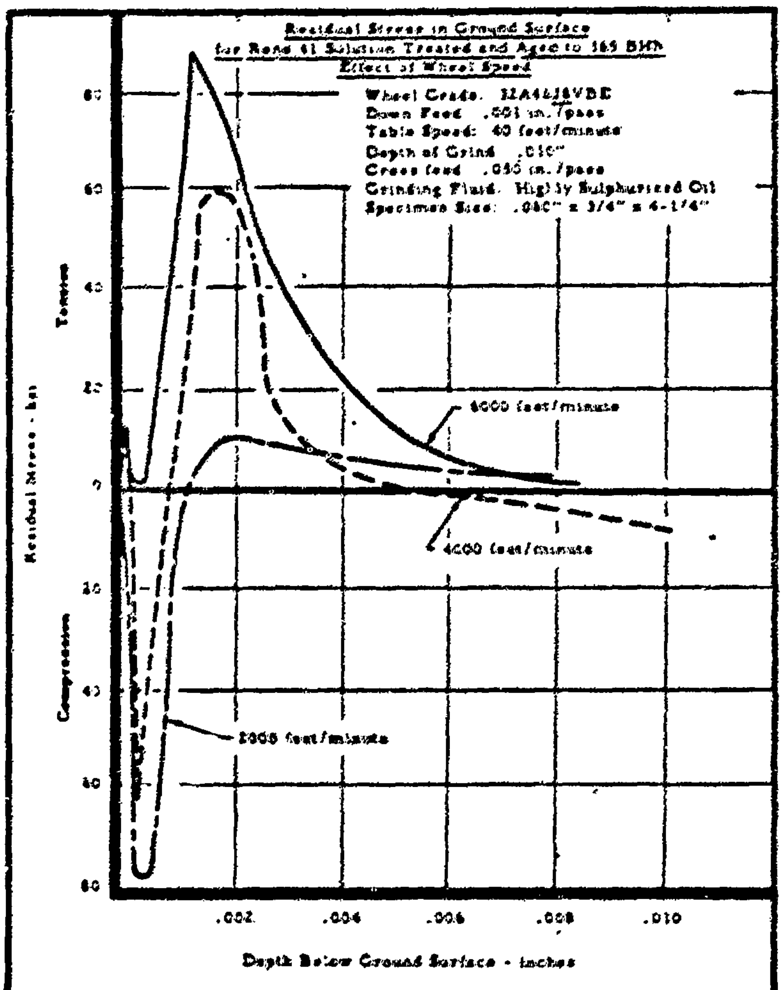


See Text, page 238

Figure 104

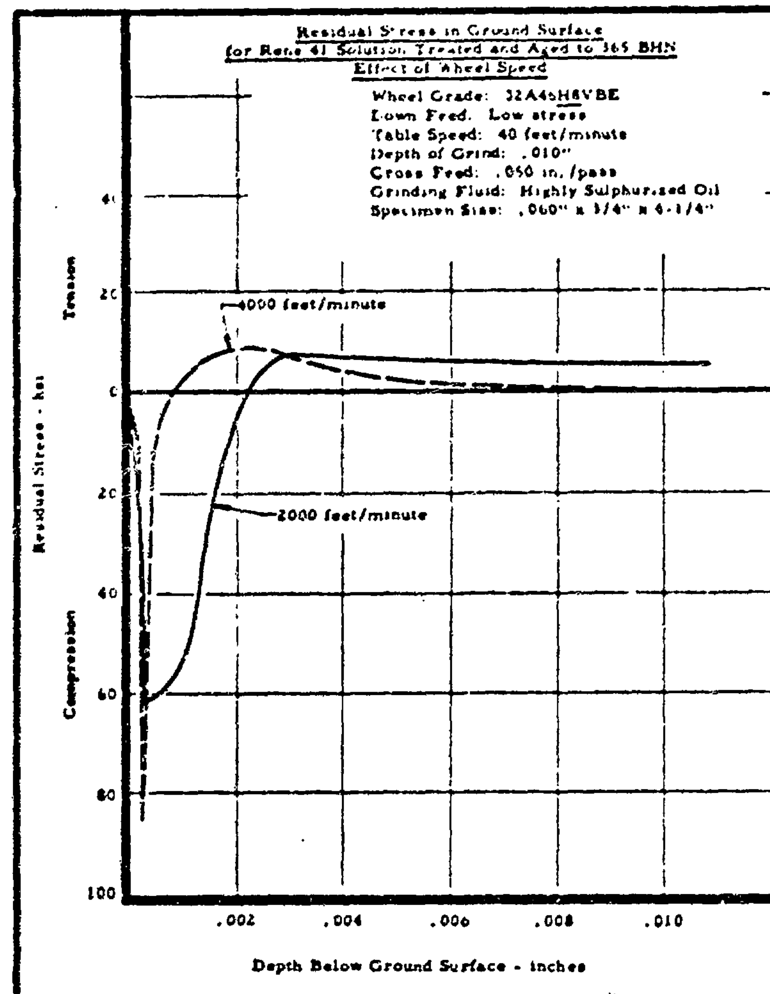


See Text, page 238



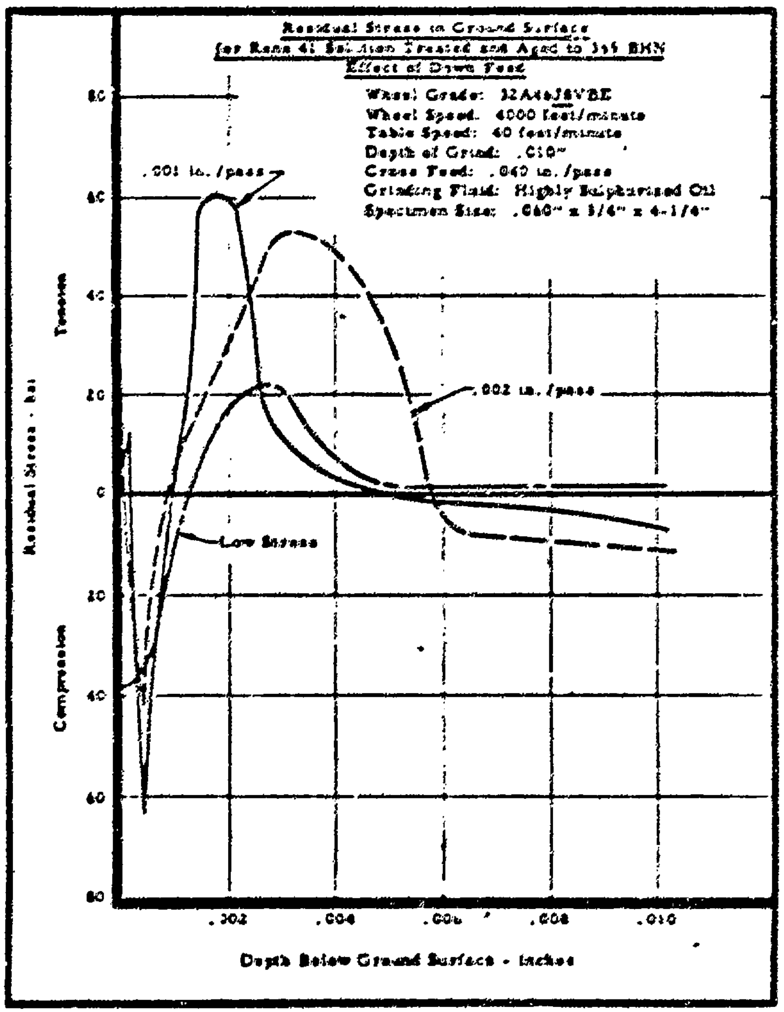
See Text, page 238

Figure 306



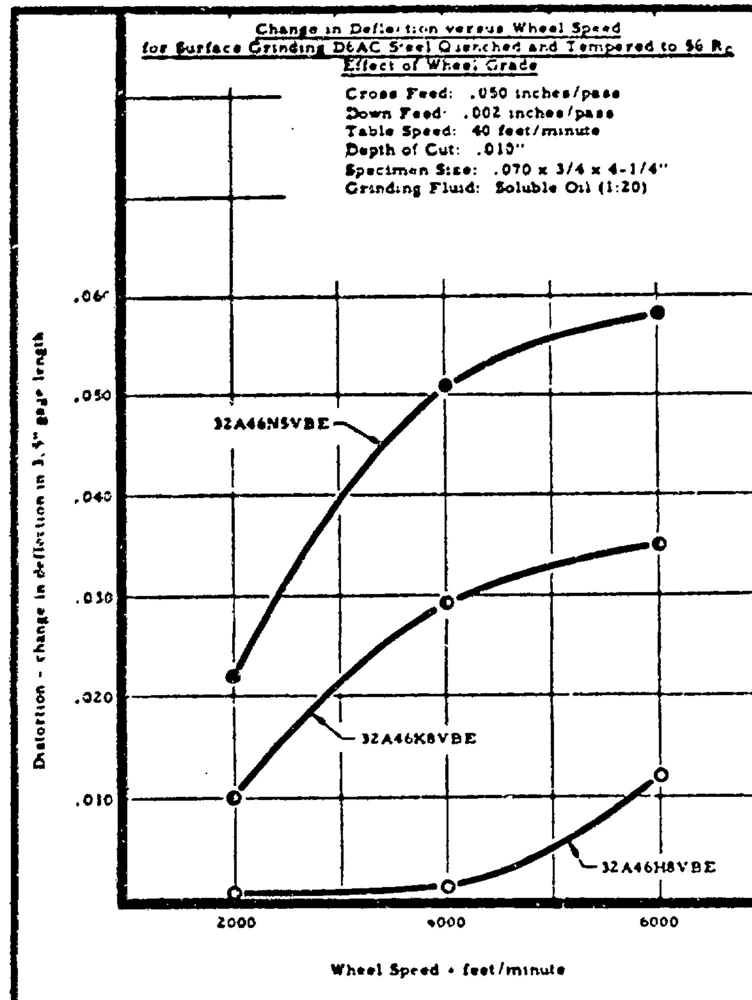
See Text, page 238

Figure 307



See Text, page 238

Figure 308



See Text, page 239

Figure 309

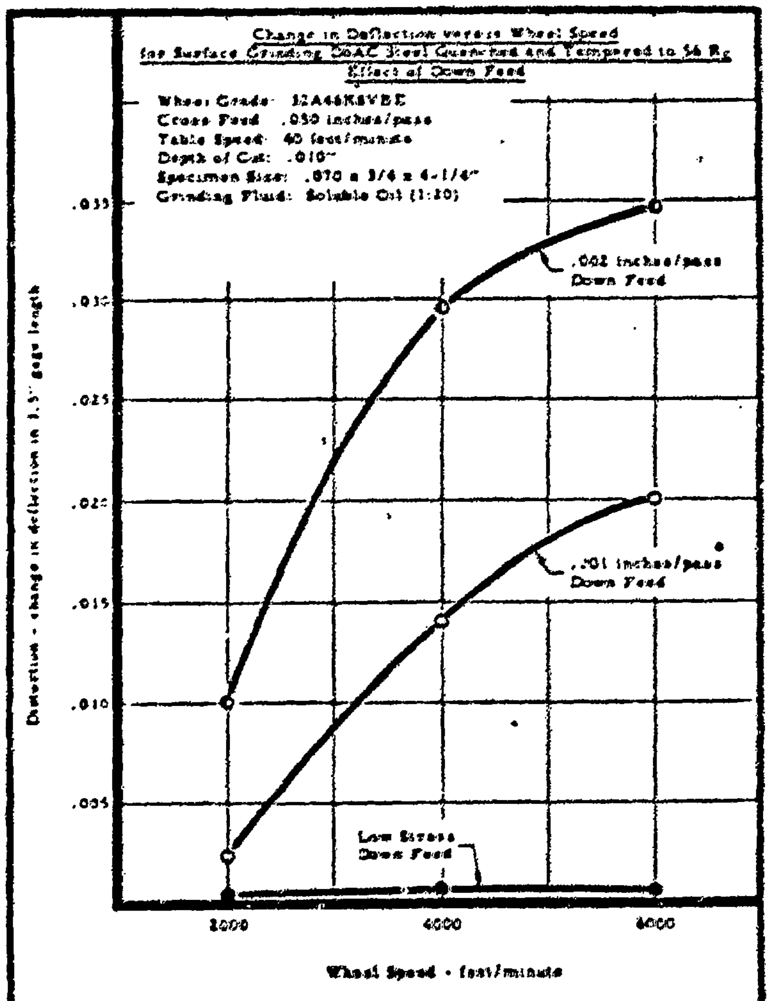


Figure 310

See Text, page 239

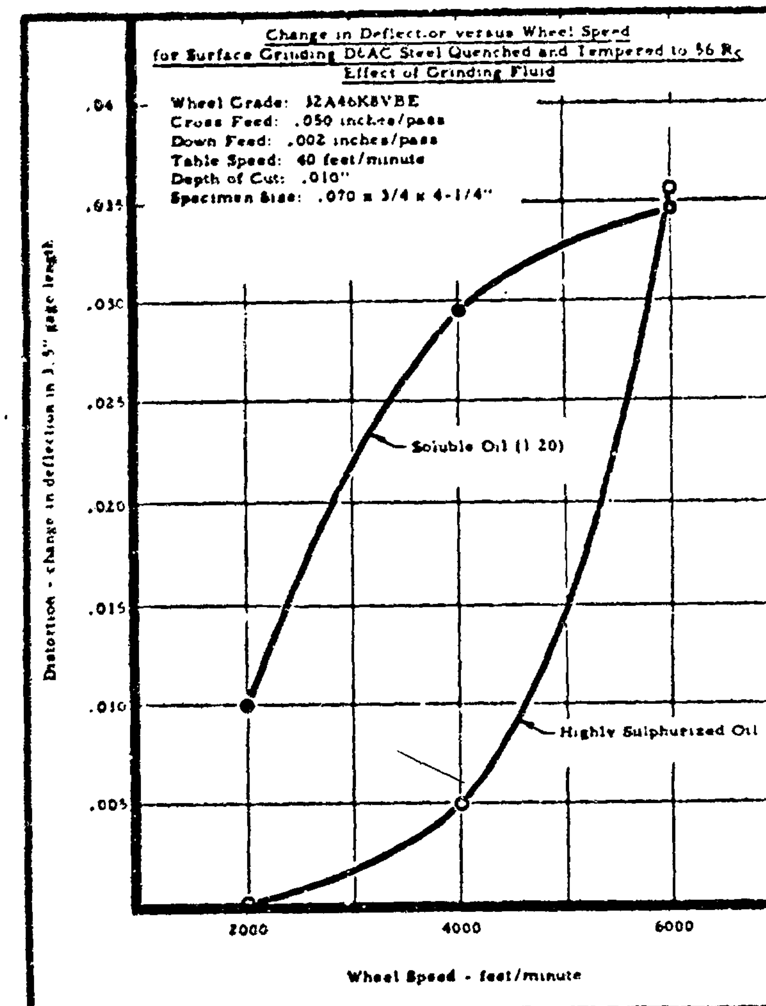
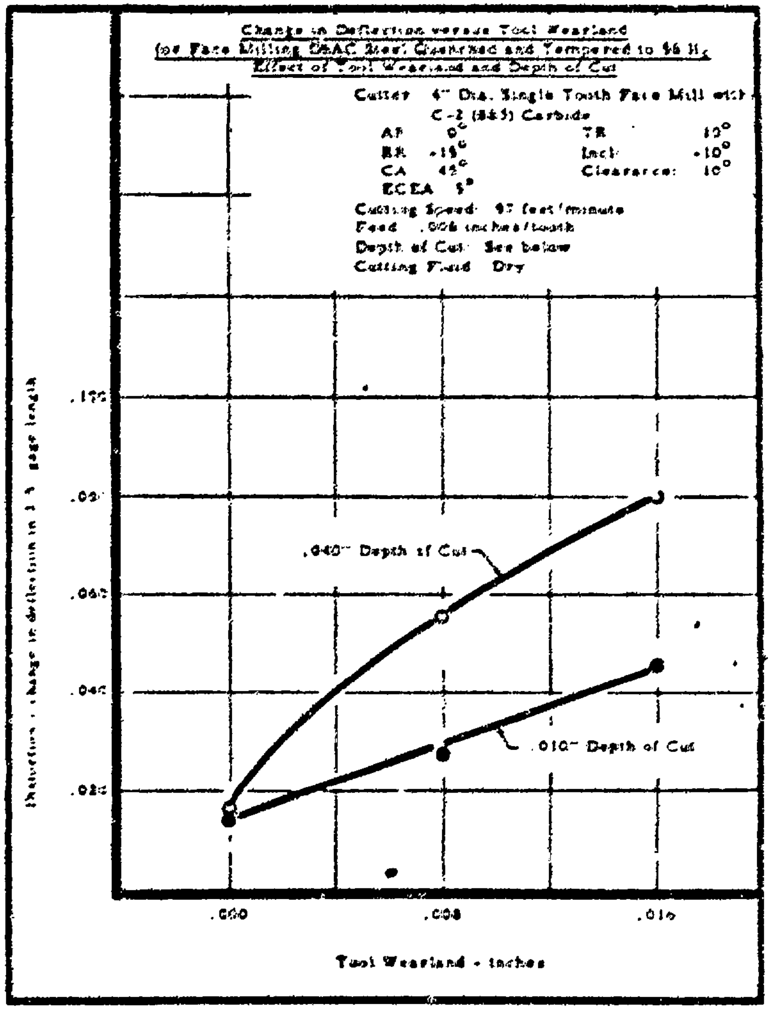
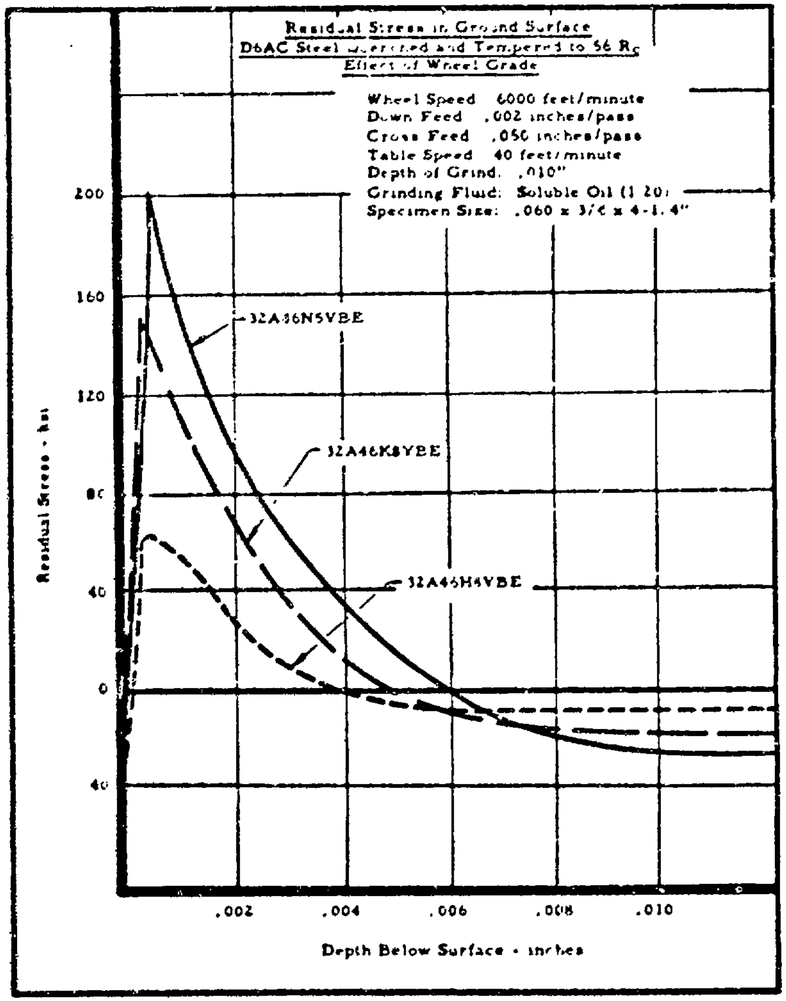


Figure 311



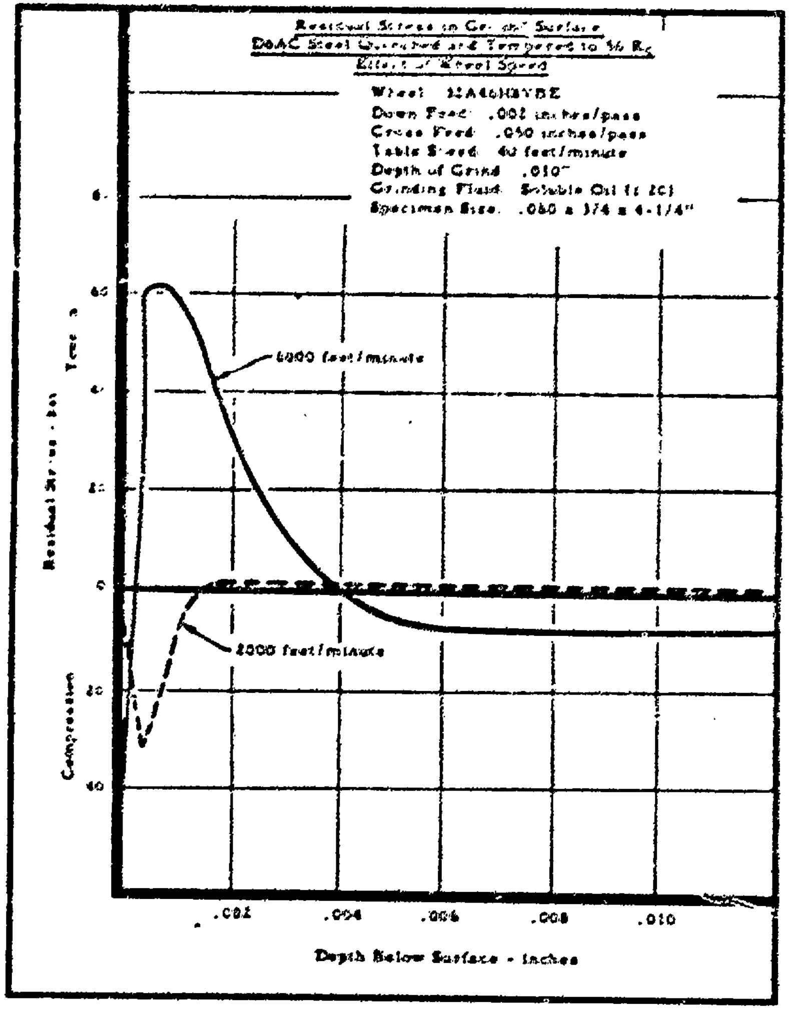
See Text, page 239

Figure 312



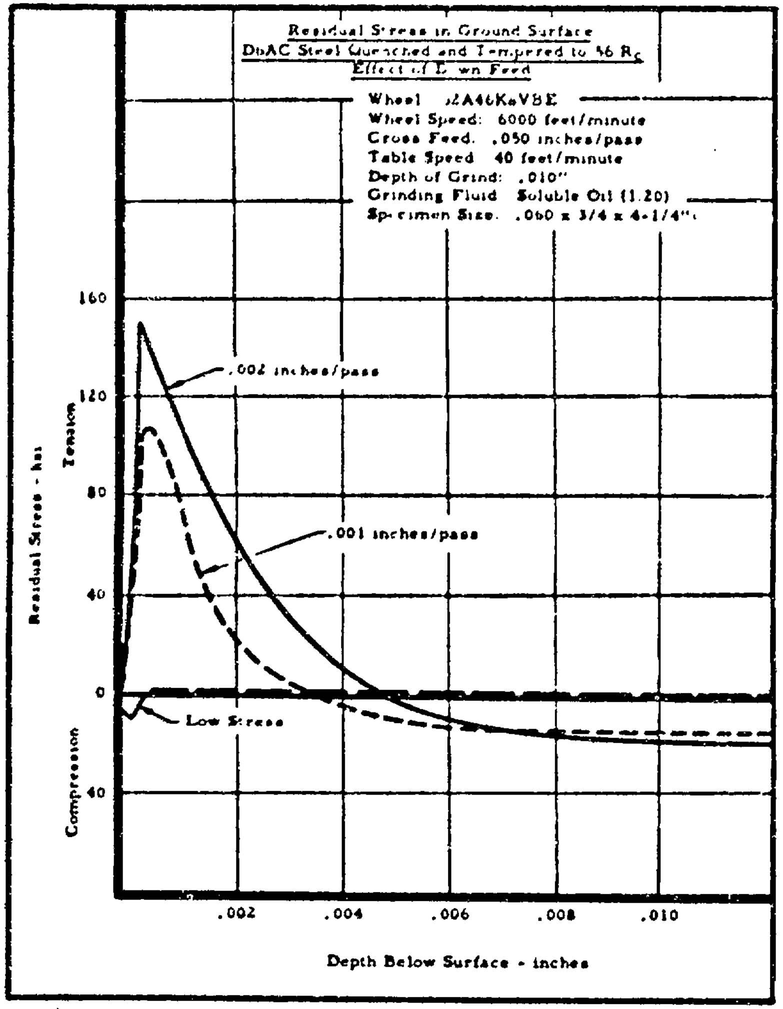
See Text, page 240

Figure 313



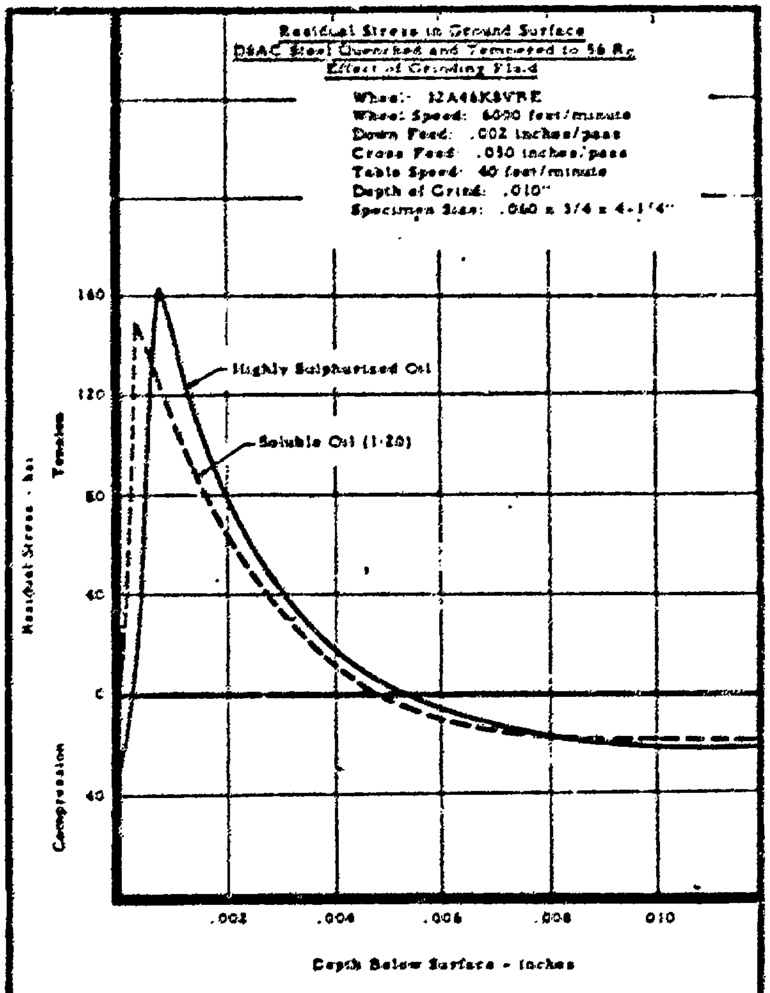
See Text, page 240

Figure 314



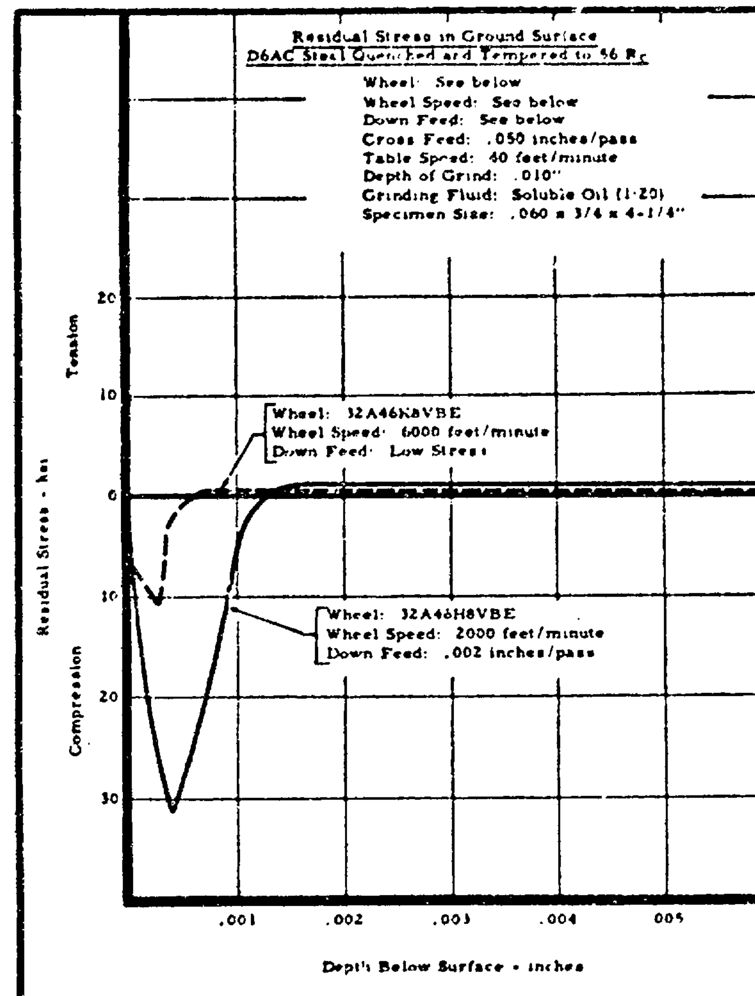
See Text, page 240

Figure 315



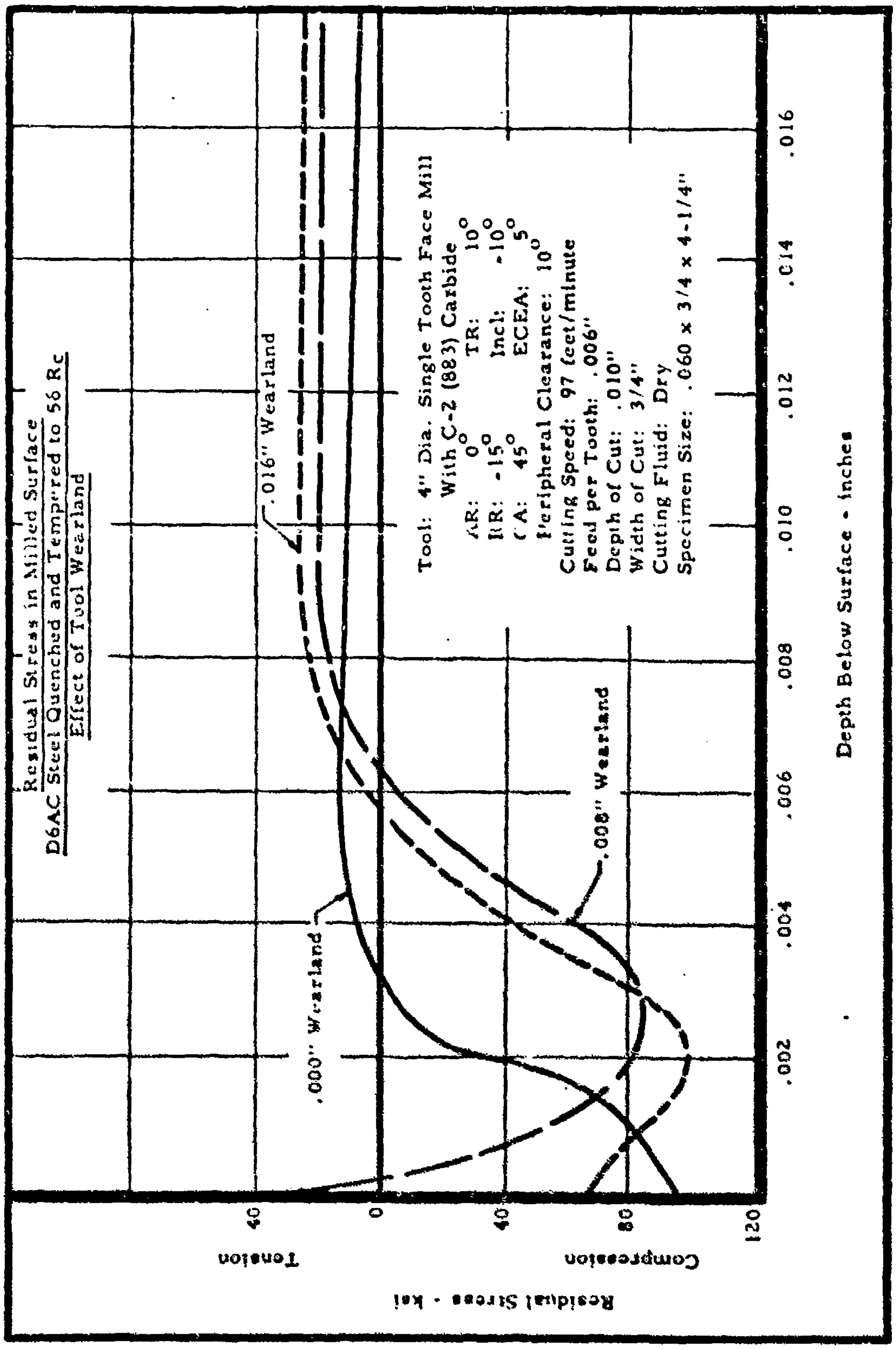
See Text, page 240

Figure 316



See Text, page 240

Figure 317



Residual Stress in Milled Surface
D6AC Steel Quenched and Temprered to 56 Rc
Effect of Tool Wearland
.016" Wearland
.008" Wearland
.000" Wearland
Tool: 4" Dia. Single Tooth Face Mill
With C-2 (883) Carbide
AR: 0° TR: 10°
RR: -15° Incl: -10°
CA: 45° ECEA: 5°
Peripheral Clearance: 10°
Cutting Speed: 97 feet/minute
Feed per Tooth: .006"
Depth of Cut: .010"
Width of Cut: 3/4"
Cutting Fluid: Dry
Specimen Size: .060 x 3/4 x 4-1/4"
Residual Stress - ksi
Tension
Compression
40
0
40
80
120
.002
.004
.006
.008
.010
.012
.014
.016
Depth Below Surface - inches

Figure 318

XII. POWER REQUIREMENTS AND COEFFICIENT OF FRICTION IN MACHINING

Force and Power Determination in Turning

The forces acting on the cutting tool during the turning operation were measured with a mechanical type dynamometer. The dynamometer measured two force components: the cutting force F_c which acts in a direction tangent to the revolving work, and the thrust force F_t which acts in a direction parallel to the axis of the rotating workpiece.

Unit power P_T, used to compare the power required for different work materials, is defined as the horsepower per unit volume of metal removed, expressed as hp/cu. in./min. In turning, unit power was computed from the following equation:

$$P_T = \frac{F_c}{396,000\ fd}$$

where F_c = cutting force measured with the tool dynamometer, pounds

f = feed, inches/rev.

d = depth of cut, inches

The coefficient of friction u between the tool face and the sliding chip can be calculated from the equation:

$$\mu = \frac{F_t + F_c \tan \alpha}{F_c - F_t \tan \alpha} *$$

where F_c = cutting force

F_t = thrust force

α = resultant rake angle

Table 18, pages 263 and 264, shows the average unit power and coefficient of friction in turning the materials tested in this program. An average unit power of about 2.5 hp/cu. in./min. was required when turning pressed and sintered, arc cast tungsten and the 90Ta-10W alloy. The TZM molybdenum and D-31 columbium alloys required an average unit power of about 1.6 hp/cu. in./min. In turning Rene 41, the average unit power was about 2.5 hp/cu. in./min while D6AC steel had an average unit power of about 3.0 hp/cu. in./min. These values were obtained using sharp tools; the unit power will increase more than 50% when the tool becomes dull.

* Nomographs for analysis of metal cutting processes - M.E. Merchant and Norman Zlatin - Mechanical Engineering, November 1945, p. 740.

Power Requirements in Drilling

The torque required in drilling was measured using a drill dynamometer. This torque dynamometer is equipped with linear differential transducers, the output of which is fed into a Sanborn Amplifier which records the torque values. The thrust force was measured using a loop dynamometer.

The unit power requirements, P_D, in drilling can be calculated from the following equation:

$$P_D = \frac{T}{50,000\ d^2 f}$$

where P_D = unit power in drilling, hp/cu. in./min.

T = torque measured with drill dynamometer inch-pounds

d = diameter of drill, inches

f = feed, inches/rev.

Table 19, page 265, shows the average unit power required when drilling the refractory alloys tested in this program. These values were obtained using sharp drills. Unit power will increase more than 25% when the drill becomes dull. The average unit power required when drilling pressed and sintered, forged and subsequently resintered and arc cast tungsten was about 2.25 hp/cu. in./min. This is about 125% higher than values that would be obtained in drilling $38R_c$ quenched and tempered steel. When drilling D-31 columbium, TZM molybdenum and the 90Ta-10W alloy, an average unit power of about 1.25 hp/cu. in./min. was required, which is about 50% lower than the values obtained for tungsten. The unit power required in drilling D6AC steel quenched and tempered to 56 R_c was about 2.10 hp/cu. in./min.

Torque and Thrust Measurements in Drilling

The torque and thrust values obtained in drilling the refractory alloys are shown in Figures 319 through 327, pages 266 through 274, for several drill sizes. Figures 319, 320 and 321, pages 266 through 268, show the drill torque and drill thrust values plotted against feed rate for three different size solid carbide drills. With a 3/8" diameter drill, the torque increased from 10 inch-pounds at a feed of .0005 in./rev. to 25 inch-pounds at a feed of .002 in./rev. The drill thrust increased proportionally. It is interesting to note that the torque and thrust values were practically the same for the three types of tungsten tested, although each type was processed differently.

The torque and thrust values obtained on D-31 columbium are shown in Figure 322, page 269. These data were obtained using M-2 HSS drills at a cutting speed of 50 ft./min. in the feed range of .002 to .009 in./rev. When using a

1/4" diameter drill with a .002 in./rev. feed, a torque of about 10 inch-pounds was obtained with a thrust of about 150 pounds. When the drill size was increased to 1/2", the torque increased to about 30 inch-pounds with a thrust value of about 325 pounds. Increasing the feed causes the torque and thrust values to go up almost linearly. When a split point was ground on the drill, the thrust force decreased approximately 25%.

Figures 323 and 324, pages 270 and 271, show the torque and thrust values obtained on TZM and Mo-0.5 Ti alloys. These values are very nearly the same as those obtained on the D-31 columbium alloy.

In drilling the 90 Ta-10W alloy, Figure 325, page 272, shows that torque and thrust are somewhat higher than the values obtained for molybedenum and columbium alloys. The drill life data presented earlier in this report also show that this alloy is more difficult to drill. It is significant to note that the torque and thrust values increased more rapidly when higher feeds were used with this alloy compared with molybdenum and columbium alloys tested.

Figures 326 and 327, pages 273 and 274, show the drill torque and drill thrust obtained on Rene 41 solution treated and solution treated and aged. The values obtained on this alloy in the two heat treated conditions were essentially the same.

TABLE 18

AVERAGE UNIT POWER AND COEFFICIENT OF FRICTION FOR TURNING REFRACTORY ALLOYS WITH SHARP TOOLS

Tool Material: Carbide

Tool Geometry: SCEA: 15° Relief: 5°
ECEA: 15° NR: 1/32
BR&SR: (See Below)

Cutting Fluid: None

Depth of Cut: .100"

Work Material	Tool Geometry	Feed Range in./rev.	Cutting Speed ft./min.	Average Coefficient of Friction	Average Unit Power hp/cu.in./min.
Pressed & Sintered Tungsten, 95% Density 34 Rc	BR: - 15°, SR: 0°	.005 - .015	200	.50	1.98
	BR: - 15°, SR: - 5°	.005 - .015	200	.44	2.33
	BR: - 15°, SR: -10°	.005 - .015	200	.37	2.64
Arc Cast Tungsten, 99% Density, 31 Rc	BR: - 15°, SR: 0°	.005 - .015	200	.44	2.05
	BR: - 15°, SR: - 5°	.005 - .015	200	.36	2.62
	BR: - 15°, SR: -10°	.005 - .015	200	.37	2.63
TZM Molybdenum, 229 BHN	BR: 0°, SR: 20°	.005 - .015	450	.83	1.46
	BR: 0°, SR: 10°	.005 - .015	450	.55	1.62
	BR: 0°, SR: 0°	.005 - .015	450	.48	2.52
D-31 Columbium, 217 BHN	BR: 0°, SR: 20°	.005 - .015	300	.80	1.18
	BR: 0°, SR: 10°	.005 - .015	300	.63	1.39
	BR: 0°, SR: 0°	.005 - .015	300	.58	1.44
90Ta-10W Alloy, 207 BHN	BR: 0° SR: 20°	.005 - .015	150	.79	1.59
	BR: 0°, SR: 10°	.005 - .015	150	.80	2.37
	BR: 0°, SR: 0°	.005 - .015	150	.77	3.01

TABLE 18 (continued)

AVERAGE UNIT POWER AND COEFFICIENT OF FRICTION FOR TURNING

Work Material	Tool Geometry	Feed Range in./rev.	Cutting Speed ft./min.	Average Coefficient of Friction	Average Unit Power hp/cu.in./min
Rene 41, Sol. Tr. 320 BHN	BR: 0°, SR: 10°	.005 - .015	50	.54	2.11
	BR: 0°, SR: 5°	.005 - .015	50	.51	2.38
	BR: - 5°, SR: - 5°	.005 - .015	50	.50	2.84
Rene 41, Sol. Tr. & Aged, 365 BHN	BR: 0°, SR: 10°	.005 - .015	50	.68	2.43
	BR: 0°, SR: 5°	.005 - .015	50	.54	2.83
	BR: - 5°, SR: - 5°	.005 - .015	50	.42	3.01
D6AC Steel, Q & T 56 R_c	BR: 0°, SR: 0°	.005 - .015	75	.47	2.70
	BR: - 5°, SR: 0°	.005 - .015	75	.48	2.95
	BR: - 15°, SR: 0°	.005 - .015	75	.44	2.97

TABLE 19

AVERAGE UNIT POWER REQUIRED FOR DRILLING REFRACTORY ALLOYS FOR SHARP DRILLS

Drill Dia.: See below

Point Grind: Plain and Notched

Cutting Fluid: Highly Chlorinated Oil

Drill Material: HSS and Carbide

Clearance Angle: 5°

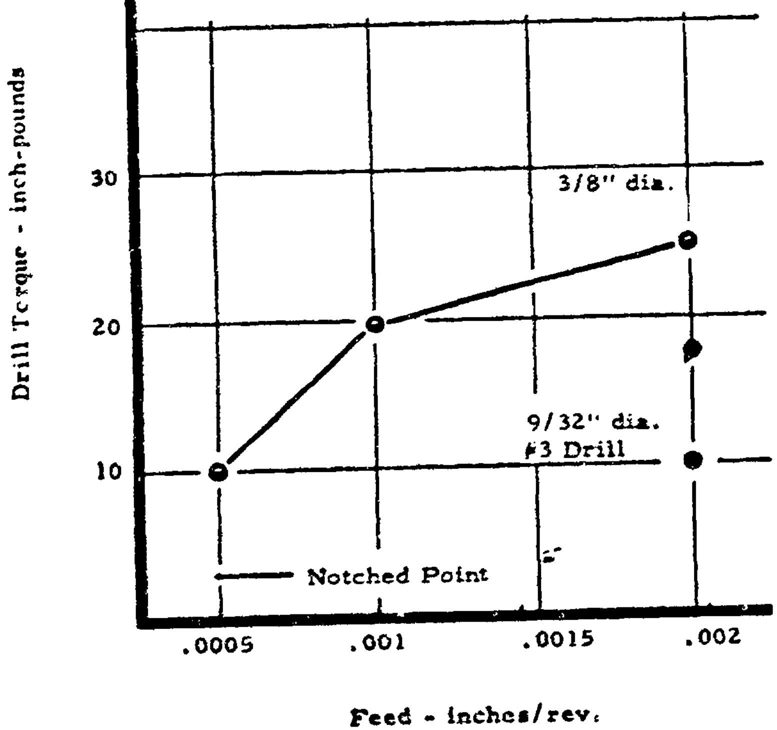
Point Angle: 118°

Helix Angle: 29°

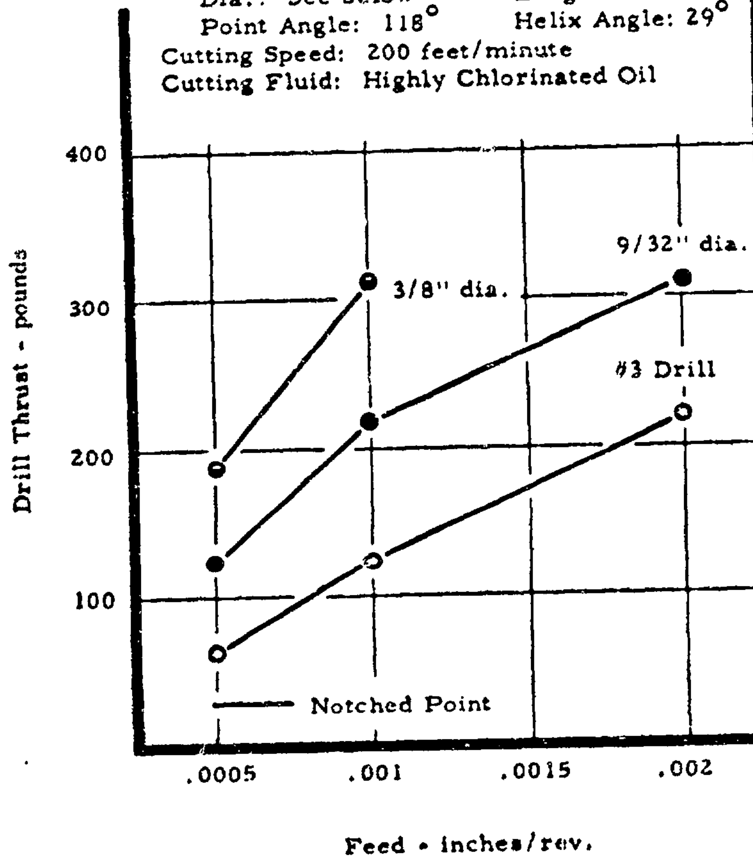
Work Material	Drill Dia.	Feed Range in./rev.	Cutting Speed ft./min.	Average Unit Power hp/cu.in./min.
Pressed & Sintered	#3	.0005-.002	200	2.20
Tungsten, 95% Density	9/32"	.0005-.002	200	2.12
34 R_c	3/8"	.0005-.002	200	2.50
Arc Cast Tungsten,	#3	.0005-.002	200	2.20
99% Density, 31 R_c	9/32"	.0005-.002	200	2.24
	3/8"	.0005-.002	200	2.28
Forged Tungsten,	#3	.0005-.002	200	2.20
96% Density, 35 R_c	9/32"	.0005-.002	200	2.20
	3/8"	.0005-.002	200	2.28
D-31 Columbium,	1/4"	.002-.009	50	1.27
217 BHN	3/8"	.002-.009	50	1.01
	1/2"	.002-.009	50	0.94
90Ta-10W Alloy,	1/4"	.002-.009	50	1.94
207 BHN	3/8"	.002-.009	50	1.37
	1/2"	.002-.009	50	1.33
TZM Molybdenum,	1/4"	.002-.009	100	1.28
229 BHN	3/8"	.002-.009	100	1.18
	1/2"	.002-.009	100	1.35
D6AC Steel,	#3	.0005-.002	150	2.10
Q&T, 56 R_c	9/32"	.0005-.002	150	2.12
	3/8"	.0005-.002	150	2.03

Drilling Pressed and Sintered Tungsten
Drill Torque and Drill Thrust

Drill: Grade 883 (C-2) Carbide
Dia.: See below Length: 3''
Point Angle: 118° Helix Angle: 29°
Cutting Speed: 200 feet/minute
Cutting Fluid: Highly Chlorinated Oil

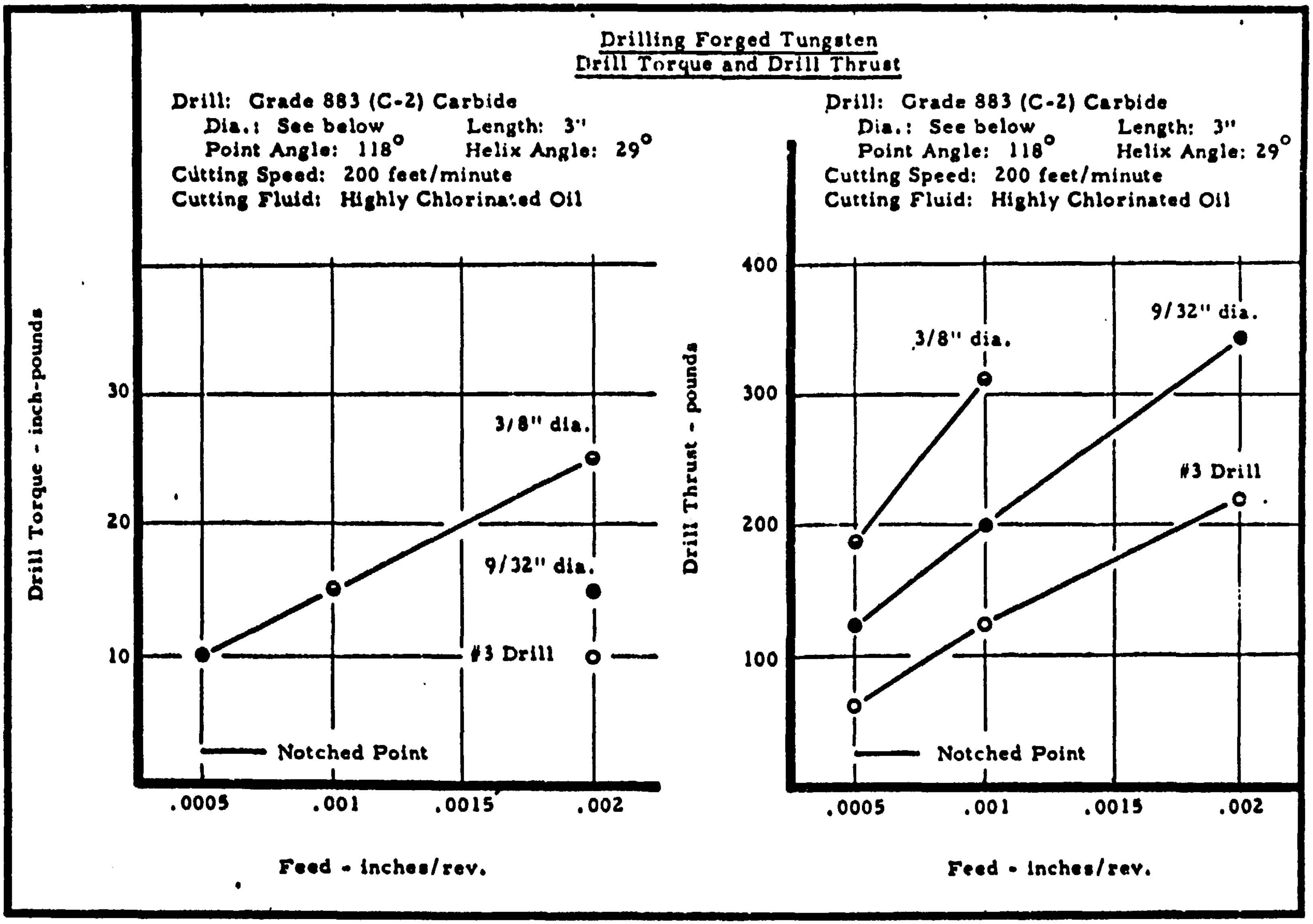


Drill: Grade 883 (C-2) Carbide
Dia.: See below Length: 3''
Point Angle: 118° Helix Angle: 29°
Cutting Speed: 200 feet/minute
Cutting Fluid: Highly Chlorinated Oil



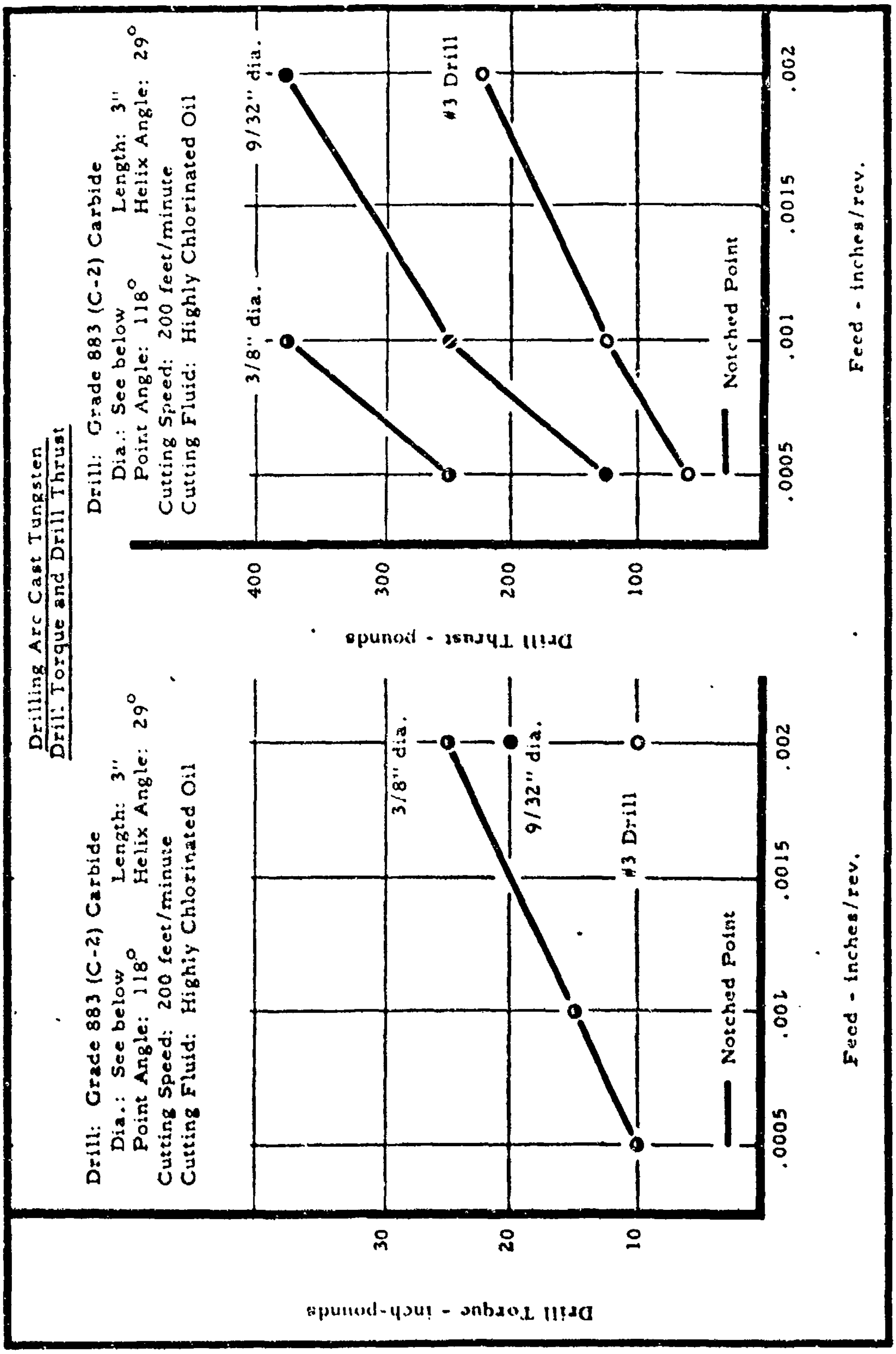
See Text page 261

Figure 319



See Text page 261

Figure 320

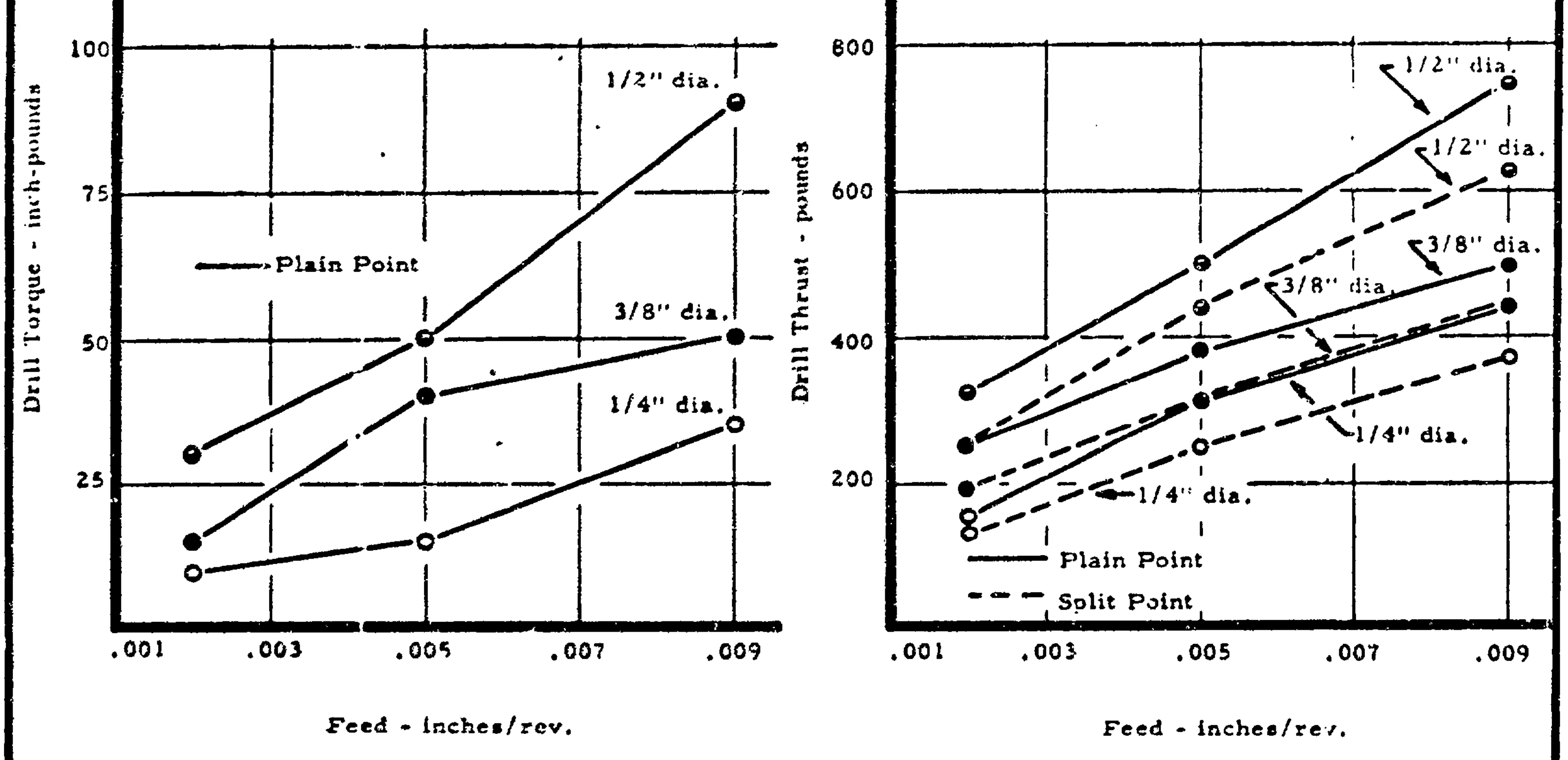


Drilling Arc Cast Tungsten
Drill: Torque and Drill Thrust
Drill: Grade 883 (C-2) Carbide
Dia.: See below Length: 3"
Point Angle: 118° Helix Angle: 29°
Cutting Speed: 200 feet/minute
Cutting Fluid: Highly Chlorinated Oil
3/8" dia.
9/32" dia.
#3 Drill
Notched Point
Drill Torque - inch-pounds
30
20
10
.0005
.001
.0015
.002
Feed - inches/rev.
Drill: Grade 883 (C-2) Carbide
Dia.: See below Length: 3"
Point Angle: 118° Helix Angle: 29°
Cutting Speed: 200 feet/minute
Cutting Fluid: Highly Chlorinated Oil
3/8" dia.
9/32" dia.
#3 Drill
Notched Point
Drill Thrust - pounds
400
300
200
100
.0005
.001
.0015
.002
Feed - inches/rev.

Drilling Columbium D-31, 207 BHN
Drill Torque and Drill Thrust

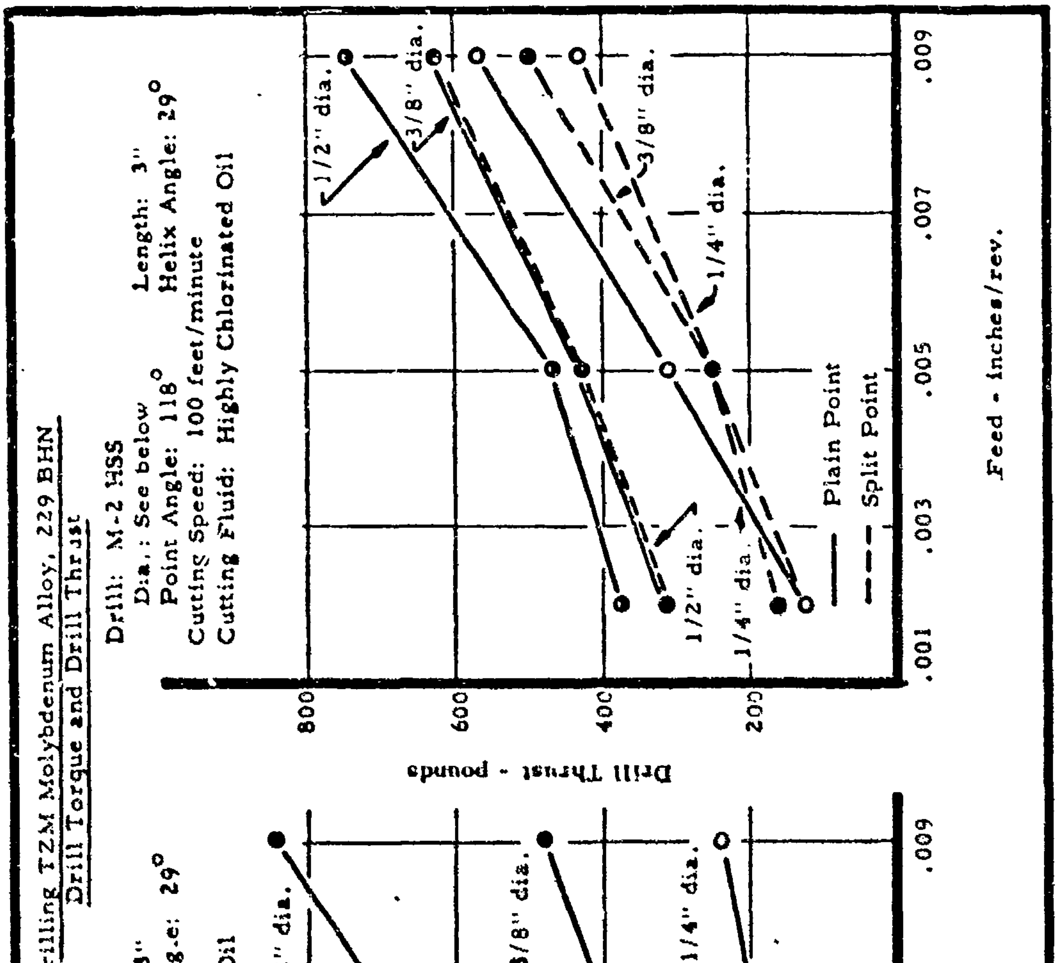
Drill: M-2 HSS
Dia.: See below Length: 3"
Point Angle: 118° Helix Angle: 29°
Cutting Speed: 50 feet/minute
Cutting Fluid: Highly Chlorinated Oil

Drill: M-2 HSS
Dia.: See below Length: 3"
Point Angle: 118° Helix Angle: 29°
Cutting Speed: 50 feet/minute
Cutting Fluid: Highly Chlorinated Oil



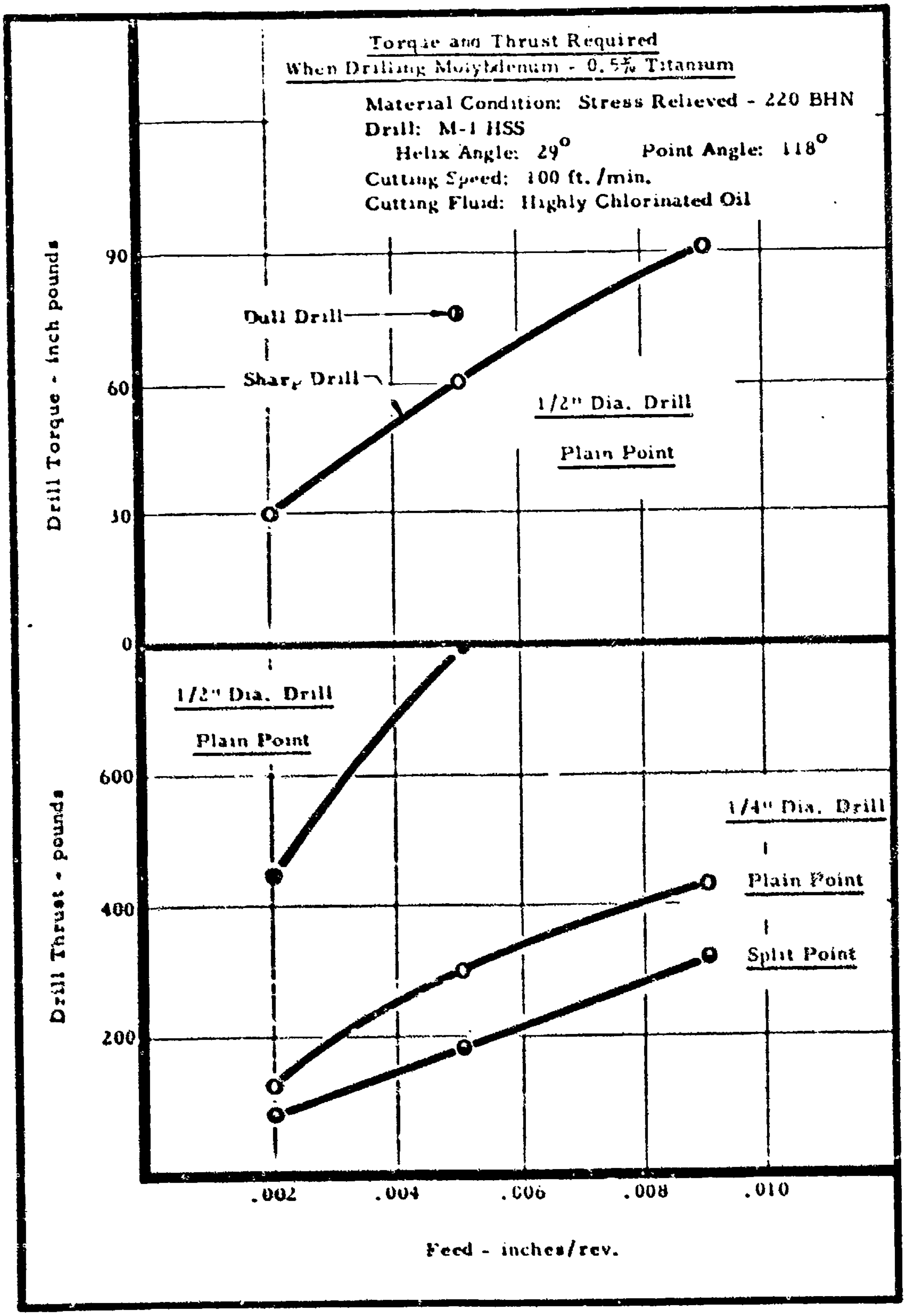
See Text page 261

Figure 322



See Text page 262

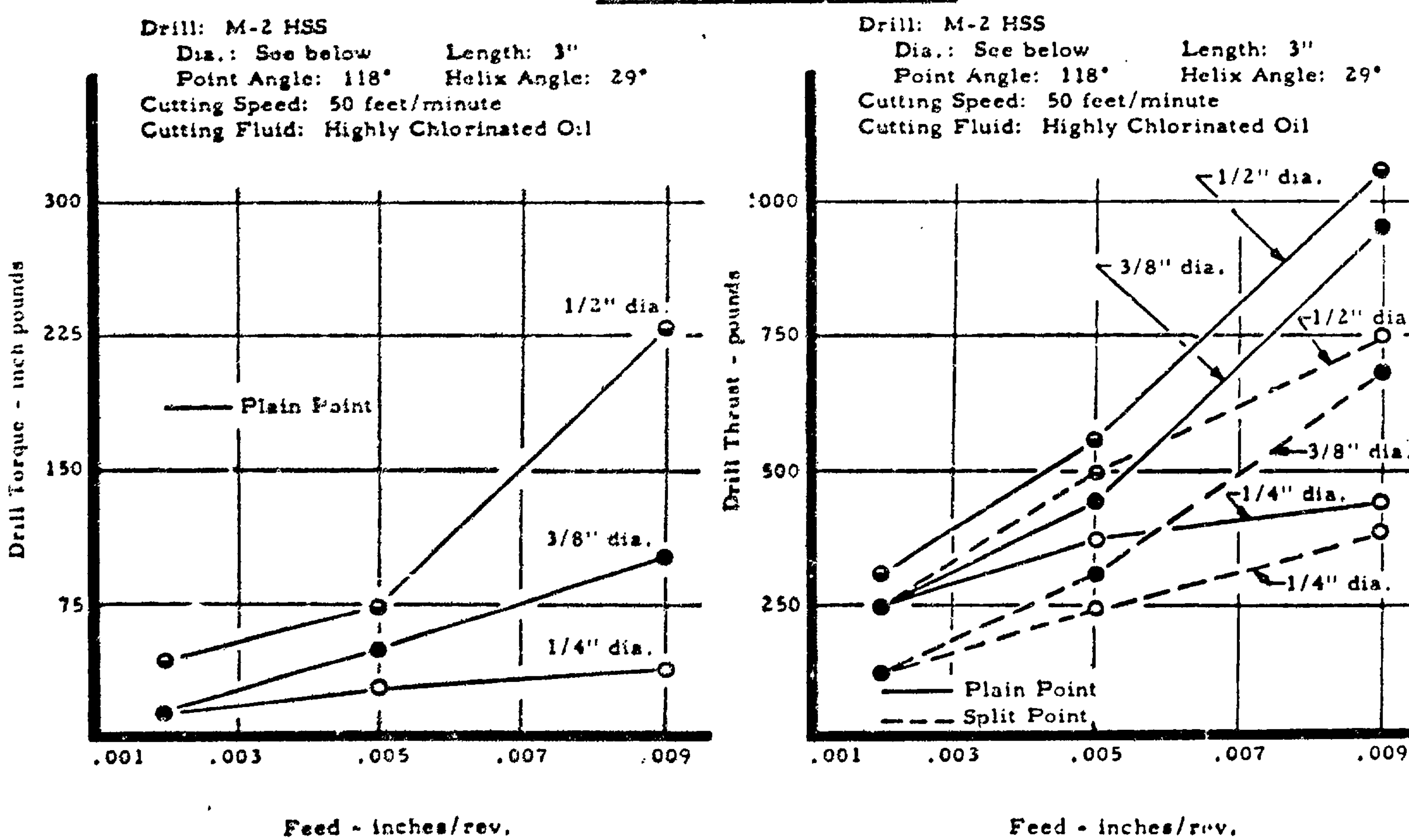
Figure 323



See Text, page 262

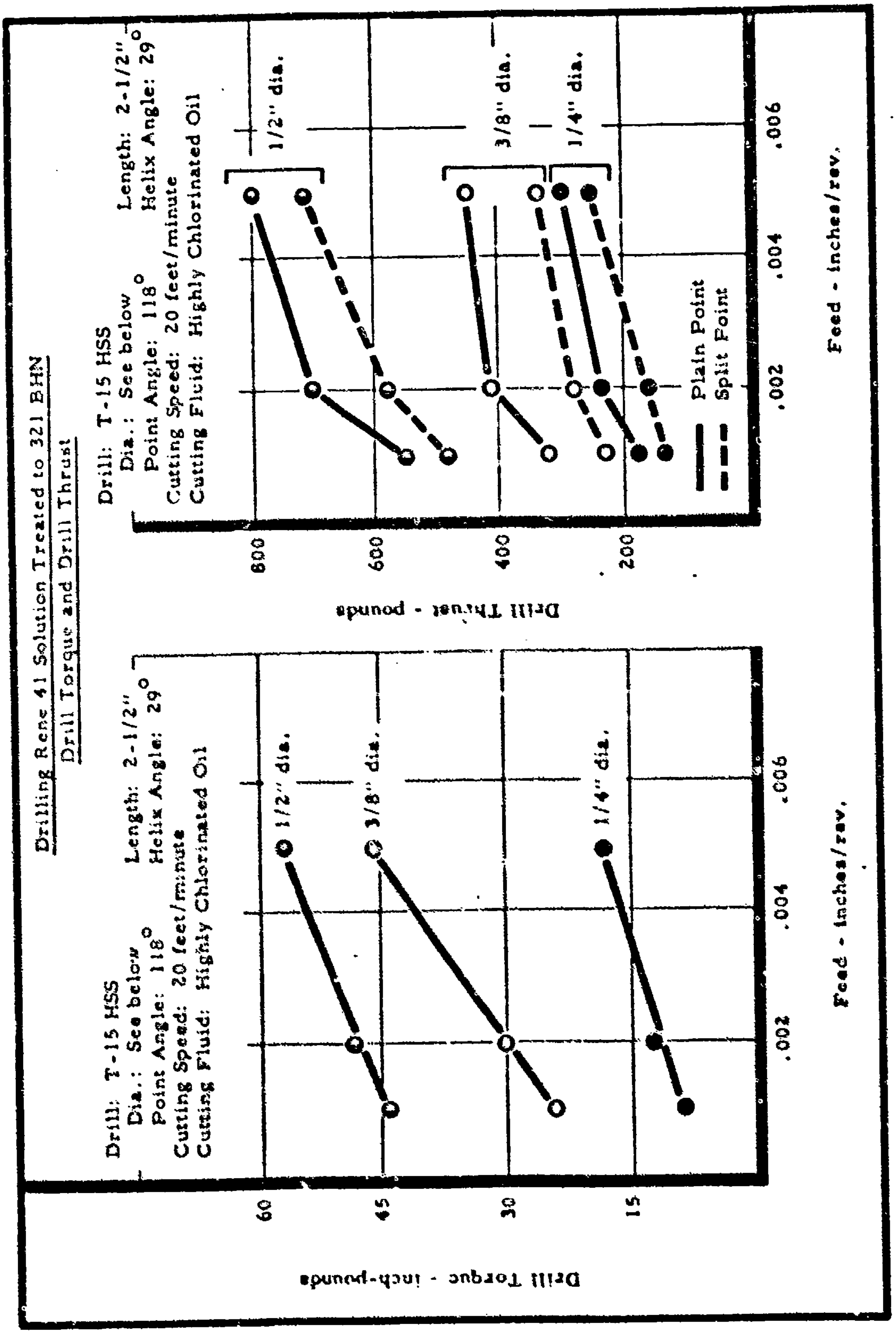
Figure 324

Drilling 90Ta-10W Alloy, 207 BHN
Drill Torque and Drill Thrust



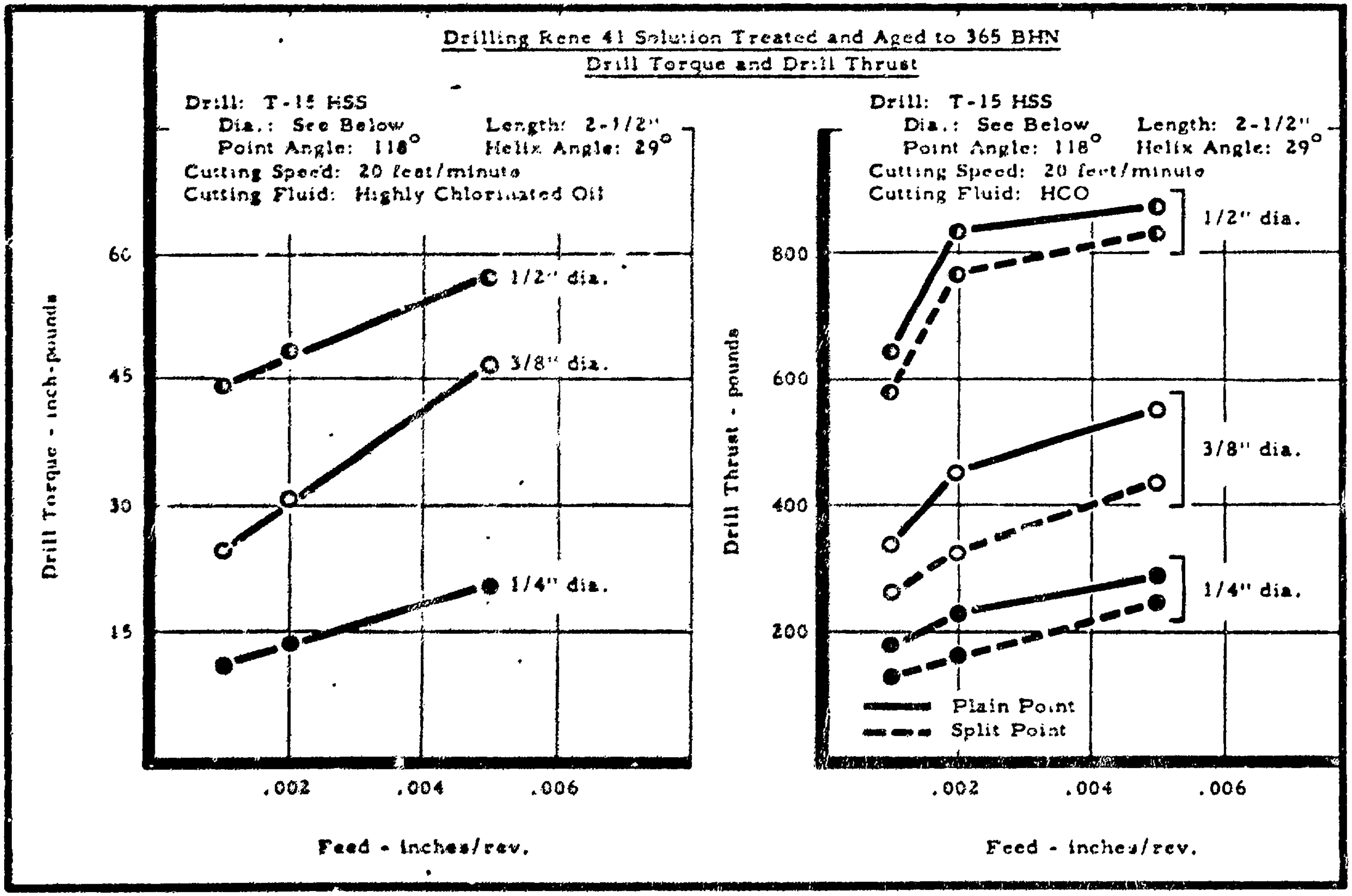
See Text, page 262

Figure 325



See Text, page 262

Figure 326



See Text, page 262

Figure 327

XIII. MACHINING NON-METALLIC MATERIALS

The main interest in the non-metallic materials lies in structural applications. These materials appear to be best suited for coatings, erosion and heat barriers for they can withstand temperatures above the limits of metals and alloys.

Composites are in common use today as heat shield materials. Ceramic coated nose cones of the ablative design are also being investigated.

The non-metallic materials studied in this program include:

1. Silica Fiber Reinforced Phenolic Resin (Refrasil)
2. Solid Zirconium Oxide
3. Flame-sprayed Zirconium Oxide Coatings
4. Flame-sprayed Aluminum Oxide Coatings
5. High Temperature Glass Ceramic (Pyroceram)

Turning, milling, drilling and tapping tests were conducted on the silica fiber reinforced phenolic resin material. The remaining four non-metallics cannot be machined with conventional cutting tools; hence, only grinding tests were conducted on these materials.

Silica Fiber Reinforced Phenolic Resin (Refrasil)

Turning Tests

The effect of cutting speed and tool material in turning this material is shown in Figure 328, page 280. A maximum tool life of 15 minutes was obtained at a cutting speed of 100 feet/minute with a feed of .009 in./rev. using a grade K-6 (C-2) carbide. When the cutting speed was increased to 200 feet/minute, tool life decreased to eight minutes and at 300 feet/minute, a tool life of three minutes was obtained. At 200 feet/minute with a grade K-7H (C-8) carbide, three minutes tool life was obtained, while a grade 370 (C-6) carbide provided one minute of tool life.

Figure 329, page 280, shows that the best feed to use when turning this material is .015 in./rev. With this feed and a cutting speed of 200 feet/minute, a tool life of 25 minutes was obtained. Tool life decreased rapidly when the feed was reduced to .005 in./rev. or increased to .022 in./rev.

Face Milling Tests

Silica reinforced phenolic resin can be face milled with carbides at very high cutting speeds. The data shown in Figure 330, page 281, was obtained at a cutting speed of 1300 feet/minute. With this cutting speed and a feed of

Face Milling Tests (continued)

.009 in./rev., the maximum tool life was 175 inches of work travel per tooth. When the feed was reduced to .004 in./tooth, tool life decreased to 105 inches per tooth, and when the feed was increased to .015 in./tooth, 140 inches of work travel was obtained.

Drilling Tests

Figure 331, page 281, shows the test data obtained when drilling this material with high speed steel drills. Best drill life, 14 holes, was obtained at a cutting speed of 25 feet/minute with a feed of .015 in./rev. using a Type M-1 HSS drill. Drill life decreased to nine holes at a cutting speed of 50 feet/minute and three holes when the cutting speed was increased to 100 feet/minute.

Very high drilling speeds can be used when drilling this material with carbide drills. The test data in Figure 332, page 282, shows that a drill life of almost 400 holes was obtained at a cutting speed of 300 feet/minute with a feed of .015 in./rev. using a grade 883 (C-2) solid carbide twist drill. Drill life decreased to 200 holes when the feed was reduced to .009 in./rev., and 75 holes when a feed of .005 in./rev. was used.

Tapping Tests

The test results in tapping silica reinforced phenolic resin is shown in Figure 333 and 334, pages 282 and 283. Maximum tap life, 45 holes, was obtained at a tapping speed of 25 feet/minute. See Figure 333, page 282. Tap life decreased to 30 holes when the cutting speed was increased to 30 feet/minute, and at a cutting speed of 41 feet/minute, 19 holes were tapped. The tap must be taken out of service as soon as the lead threads are worn; otherwise, the resulting threads will become torn and ragged.

Figure 334, page 283, shows the effect of tap design in tapping this material. A 4 flute plug tap is slightly better than a 2 flute chip driver tap. The 4 flute tap provided 45 holes at a cutting speed of 25 feet/minute, while the 2 flute chip driver tap provided 35 holes at this same cutting speed.

Surface Grinding Tests

Surface grinding this material presented no problem with respect to grindability. With a silicon carbide grinding wheel operating at 6000 feet/minute, more than five cubic inches of material was removed from the workpiece with no measurable wheel wear.

The dust generated in grinding presents a health problem. A suitable exhaust system should be used to collect the dust.

Surface Grinding Tests (continued

Silicon carbide grinding wheels perform best when grinding this material. Wheel speeds of 5000 to 6000 feet/minute can be used without burning. Similarly, down feeds of .010 to .025 in./pass were made without any signs of burns in the workpiece. Table speeds and cross feeds can be varied within wide limits without affecting the surface finish.

Solid Zirconium Oxide, 70% and 99% Density

Surface Grinding Tests

Only grinding tests were conducted on the solid zirconium oxide material since it cannot be machined with conventional cutting tools.

The results of the surface grinding tests performed on solid zirconium oxide are presented in Figures 335 through 338, pages 283 through 285. The 70% dense material could be ground considerably better than the 99% dense material. Figure 335, page 283, shows the effect of wheel speed. With a GC60J6VP silicon carbide grinding wheel operating at 2000 feet/minute, a G ratio of nine was obtained on the 99% dense material, while a G ratio of 84 was obtained on the 70% dense material.

These tests were performed with a nitrite solution to hold down the dust. When grinding the 70% density material dry, the grinding ratio was reduced to about 70. A grinding ratio of about five was obtained when grinding dry on the 99% dense material.

The wheel speed has considerably more effect on the grinding ratio when grinding the 70% dense material than on the 99% dense zirconium oxide. The G ratio decreased from 80 to 28 when the wheel speed was increased from 2000 feet/minute to 5000 feet/minute for the 70% dense material. However, the G ratio remained about the same for the 99% density zirconium oxide when the wheel speed was increased through the same range.

The effect of down feed is shown in Figure 336, page 284. A G ratio of about 12 was obtained over a down feed range of .002 to .004 in./pass for the 99% dense material. The G ratio decreased to about seven when the down feed was increased to .005 in./pass. When grinding the 70% dense material, the effect of down feed is much more pronounced. The grinding ratio increased from 27 to 53 when the down feed was increased from .002 to .004 in./pass. But when the down feed was increased to .005 in./pass, the G ratio decreased to about 35.

Figure 337, page 284, shows that no change in grinding ratio was observed when the table speed was increased from 20 feet/minute to 60 feet/minute when surface

Surface Grinding Tests (continued)

grinding the 99% dense material. The G ratio did increase significantly, however, when grinding the 70% dense material as the table speed was increased from 20 feet/minute to 60 feet/minute.

Figure 338, page 285, shows the effect of cross feed when grinding solid zirconium oxide. Again, no appreciable change in G ratio was observed when the cross feed was increased from .025 in./pass to .100 in./pass for the 99% dense material. However, the G ratio increased from about 30 to 90 over the same cross feed increase when grinding the 70% density material.

Flame-sprayed Zirconium Oxide and Aluminum Oxide Coatings

Surface Grinding Tests

Neither of these two coatings can be machined other than by grinding. Hence, only grinding tests were conducted.

Figure 339, page 285, shows the grinding ratios for the flame-sprayed zirconium oxide and aluminum oxide coatings. Using a 39C60J8VK silicon carbide grinding wheel operating at 5000 feet/minute with a down feed of .002 in./pass and a table speed of 20 feet/minute, a G ratio of 80 was obtained on the zirconium oxide coating and 19 on the aluminum oxide coating. These tests were made using a nitrite grinding solution to hold down the dust.

The effect of wheel grade in grinding the flame-sprayed aluminum oxide coating is shown in Figure 340, page 286. This chart shows that a medium hardness "J" silicon carbide wheel performed better than a harder "N" wheel when using the same grinding conditions. A G ratio of 19 was obtained from the "J" hardness wheel and a G ratio of nine for the "N" wheel when operating at a wheel speed of 5000 feet/minute and a down feed of .002 in./pass. In grinding the flame-sprayed aluminum oxide, the G ratio was more than doubled when using a nitrite solution, compared to grinding dry.

High Temperature Glass Ceramic (Pyroceram)

Surface Grinding Tests

Only grinding tests were conducted on this material since it is not machinable by conventional cutting tools.

The results of the grinding tests performed on pyroceram are given in Figures 341 through 345, pages 286 through 288. In grinding this material, silicon carbide wheels produced higher G ratios than aluminum oxide wheels. See

Surface Grinding Tests (continued)

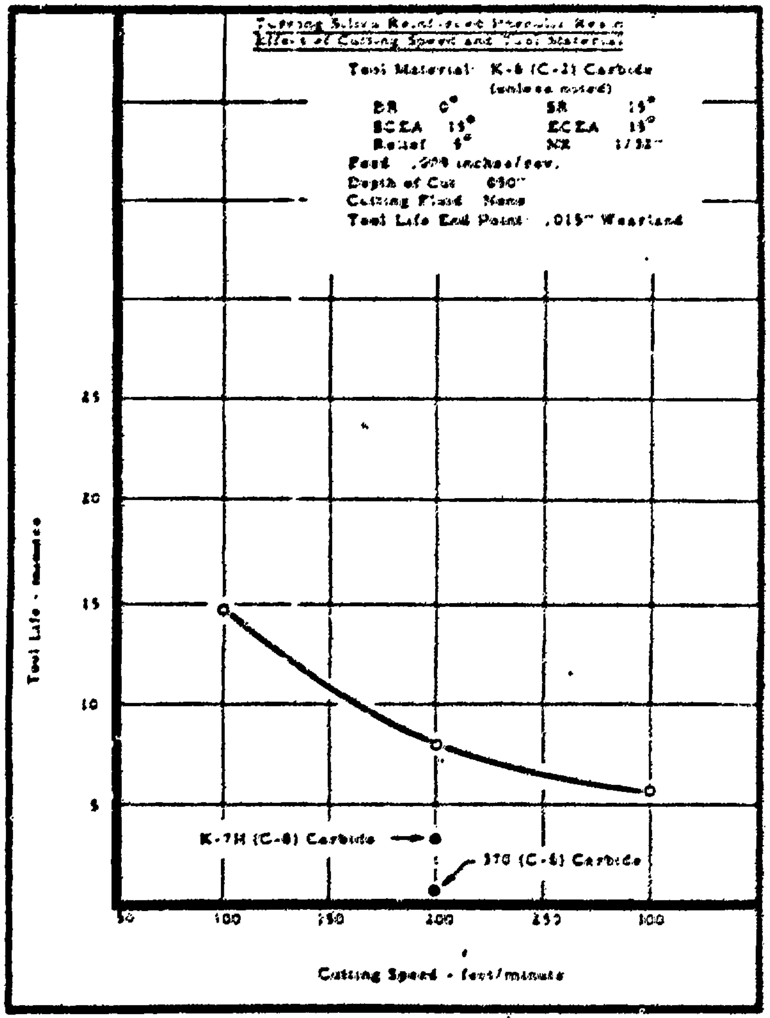
Figure 341, page 286. The highest G ratio, 35, was obtained using a GC60J6VP silicon carbide wheel. A G ratio of eight was obtained with a 32A46N5VBE aluminum oxide wheel at a wheel speed of 5000 feet/minute and a down feed of .002 in./rev. using a 5% nitrite grinding solution.

The effect of wheel speed is shown in Figure 342, page 287, using both a silicon carbide and an aluminum oxide grinding wheel. The G ratio increased from 17 to 35 for the silicon carbide wheel when the wheel speed was increased from 2000 to 4000 feet/minute. A smaller increase in G ratio was observed for the aluminum oxide wheel when the wheel speed was increased from 2000 to 5000 feet/minute.

In grinding the Pyroceram with a silicon carbide grinding wheel, increasing the down feed from .002 to .005 in./pass resulted in a drastic decrease in G ratio. With a GC60J6VK wheel, a grinding ratio of 34 was produced at a down feed of .002 in./pass. When the down feed was increased to .005 in./pass, the G ratio decreased to eight. See Figure 343, page 287.

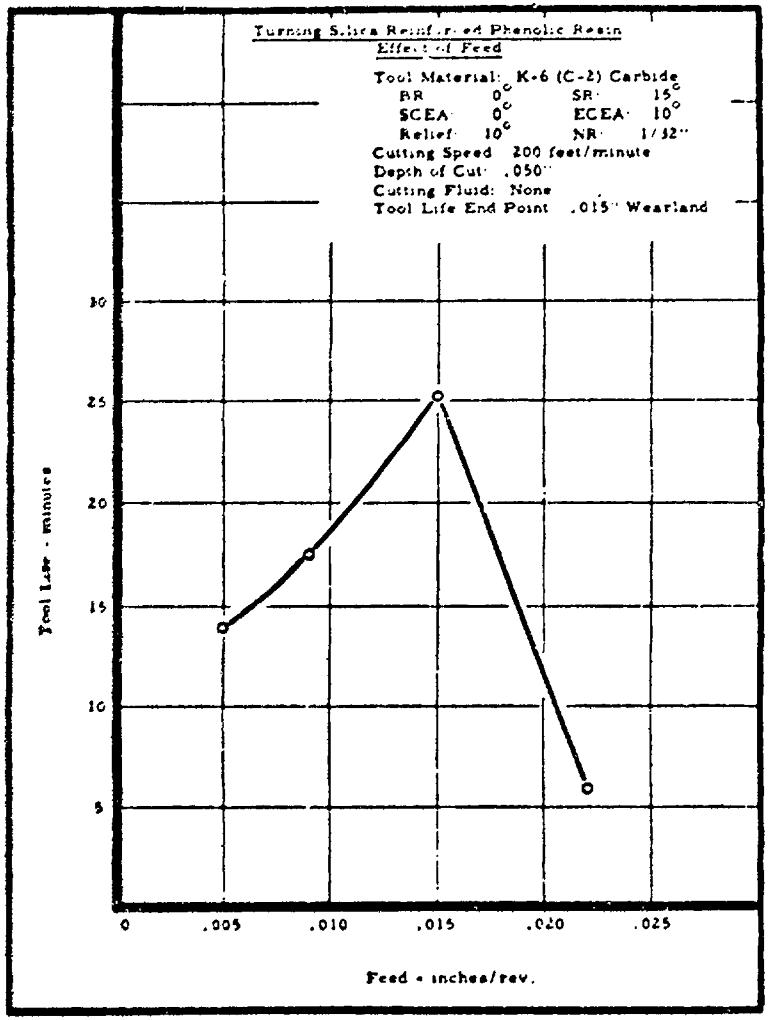
The effect of cross feed presented in Figure 344, page 288, shows that for the silicon carbide wheel changing the down feed from .025 to .050 in./pass produced no appreciable change in G ratio. When the down feed was increased to .100 in./pass, however, the grinding ratio was reduced from 35 to 11. With an aluminum oxide wheel, the G ratio decreased from seven to two when the cross feed was increased from .025 to .100 in./pass.

Low table speeds produced higher G ratios in surface grinding Pyroceram, see Figure 345, page 288. A grinding ratio of 35 was obtained when using a table speed of 20 feet/minute with a silicon carbide grinding wheel operating at 5000 feet/minute at a feed of .002 in./pass. When the table speed was increased to 40 feet/minute, the grinding ratio was reduced to 12, and at 60 feet/minute, the G ratio was reduced to six.



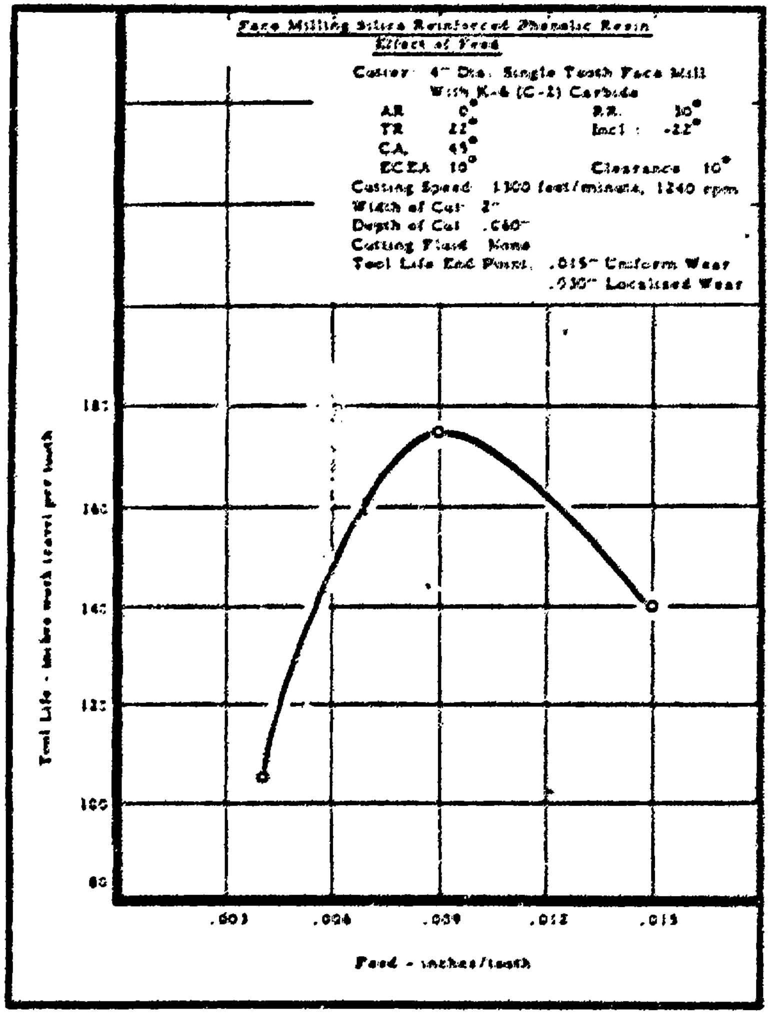
See Text page 275

Figure 128



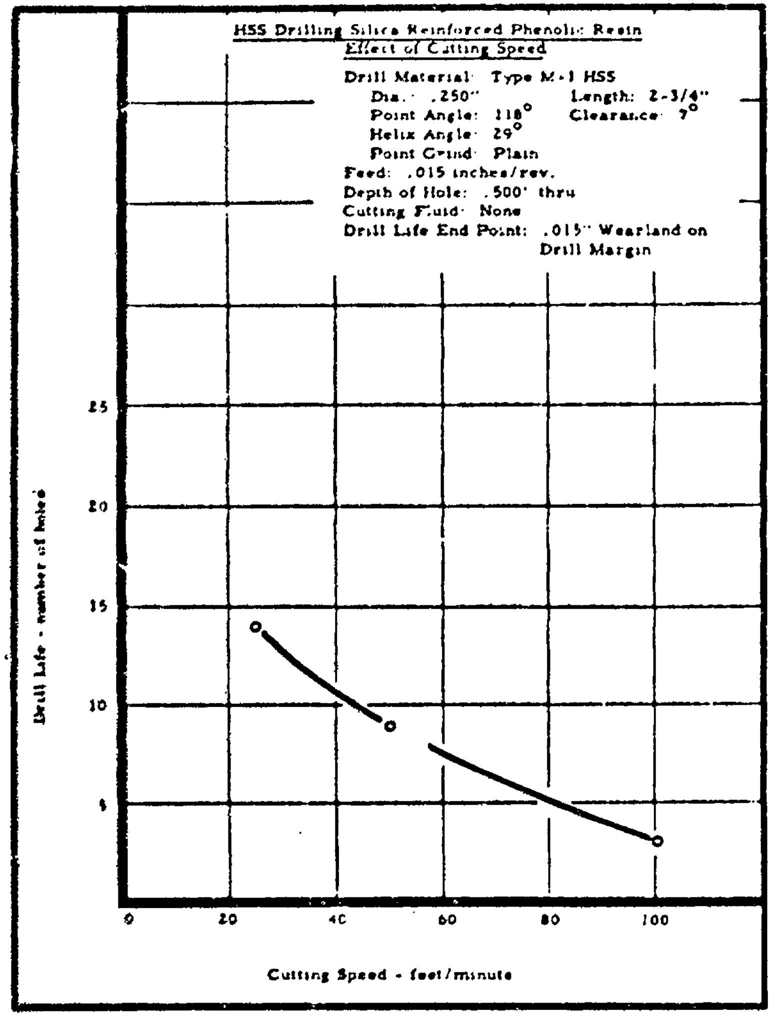
See Text page 275

Figure 129



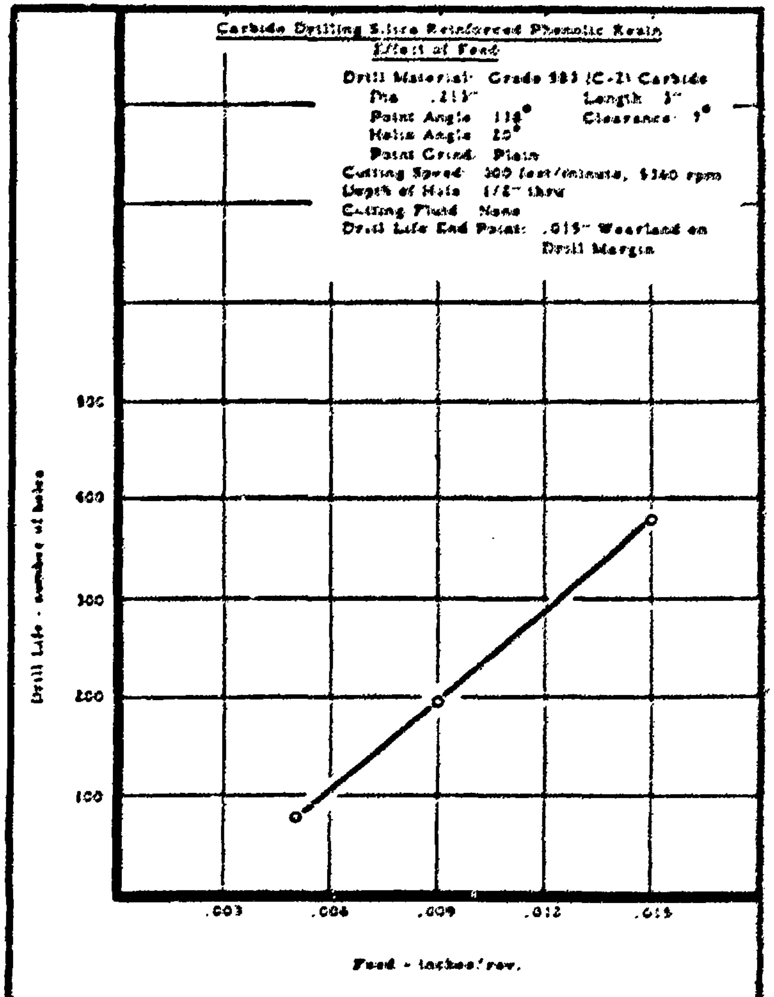
See Text page 275

Figure 332



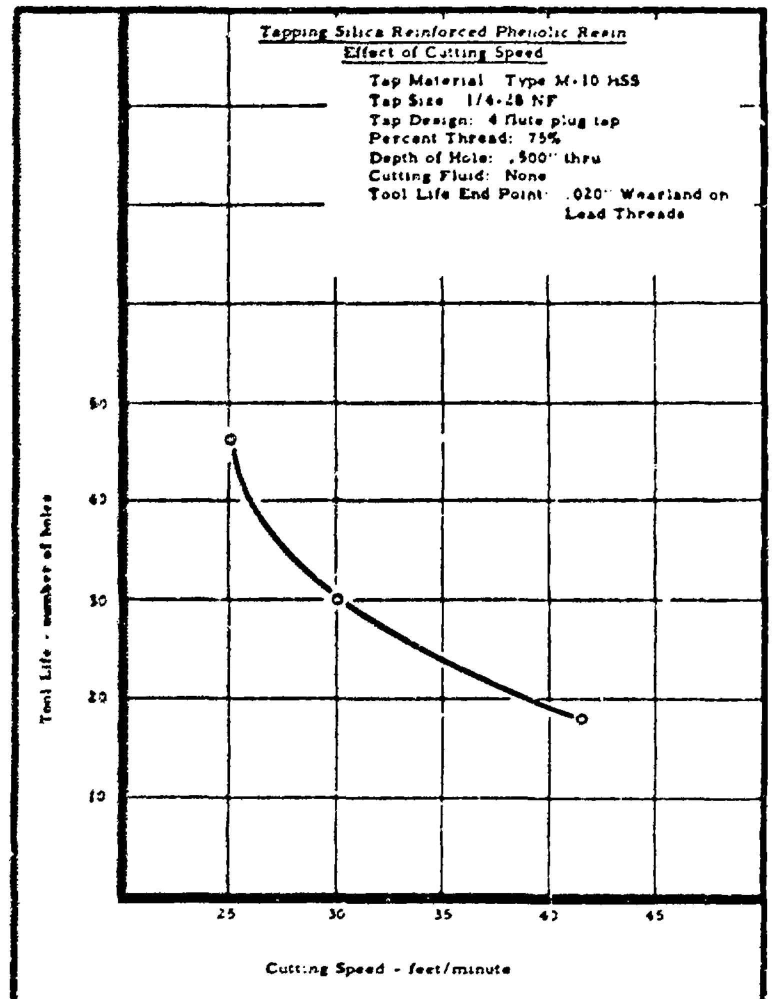
See Text page 276

Figure 331



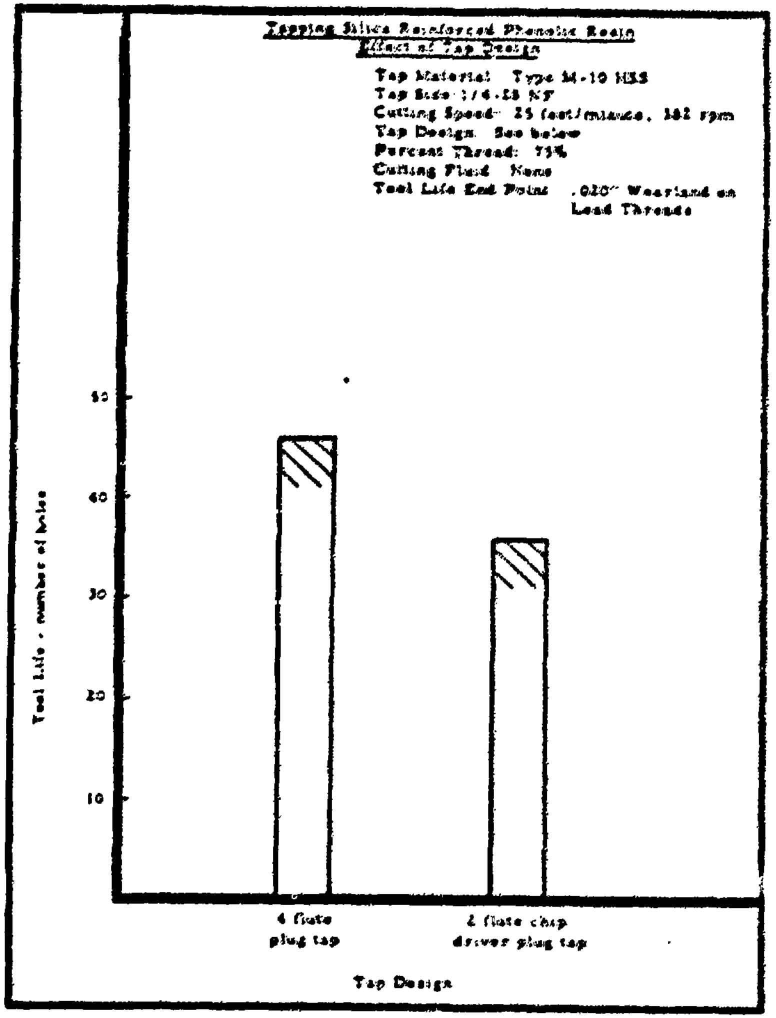
See Text page 276

Figure 332



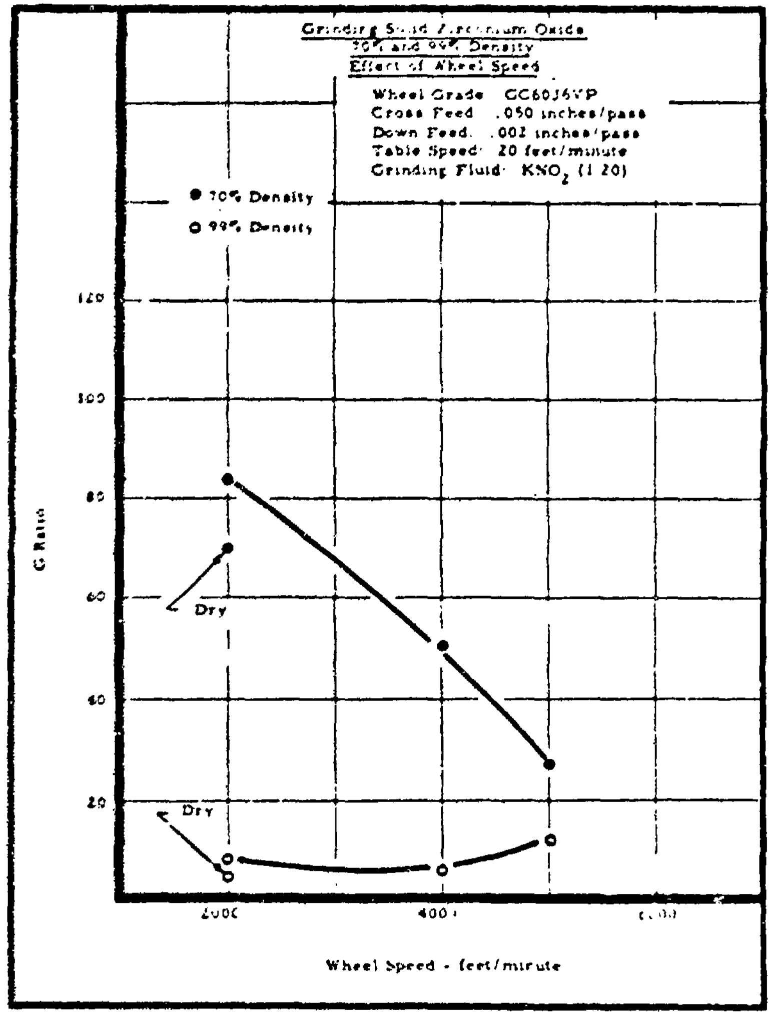
See Text page 276

Figure 333



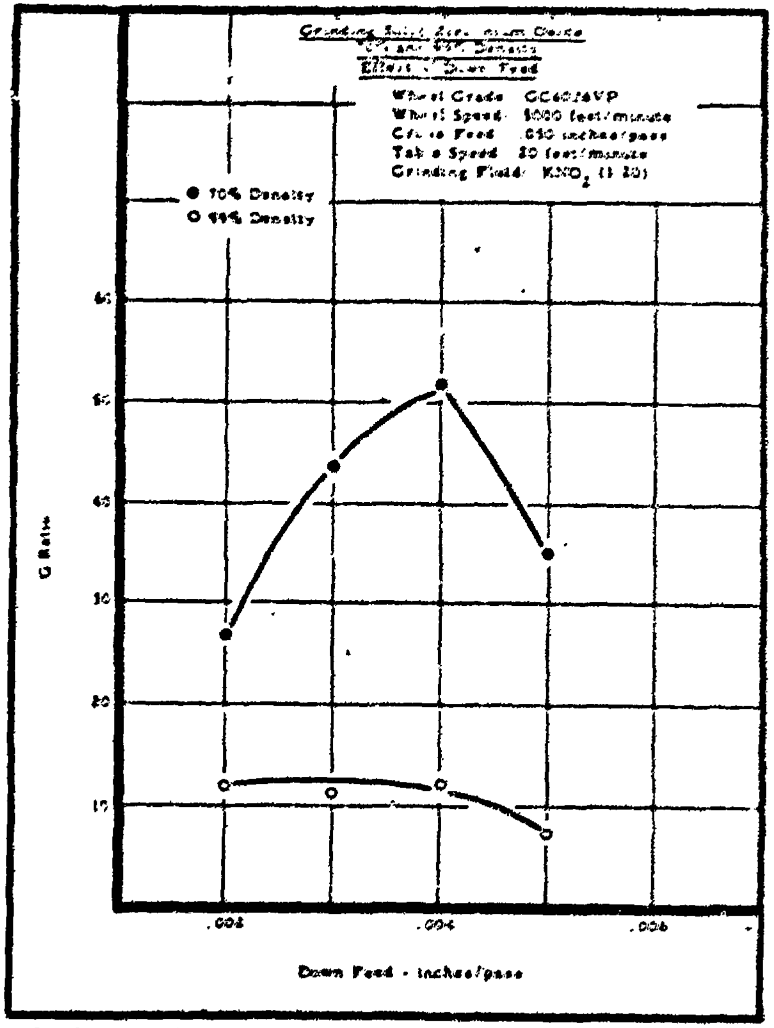
See Text page 276

Figure 334



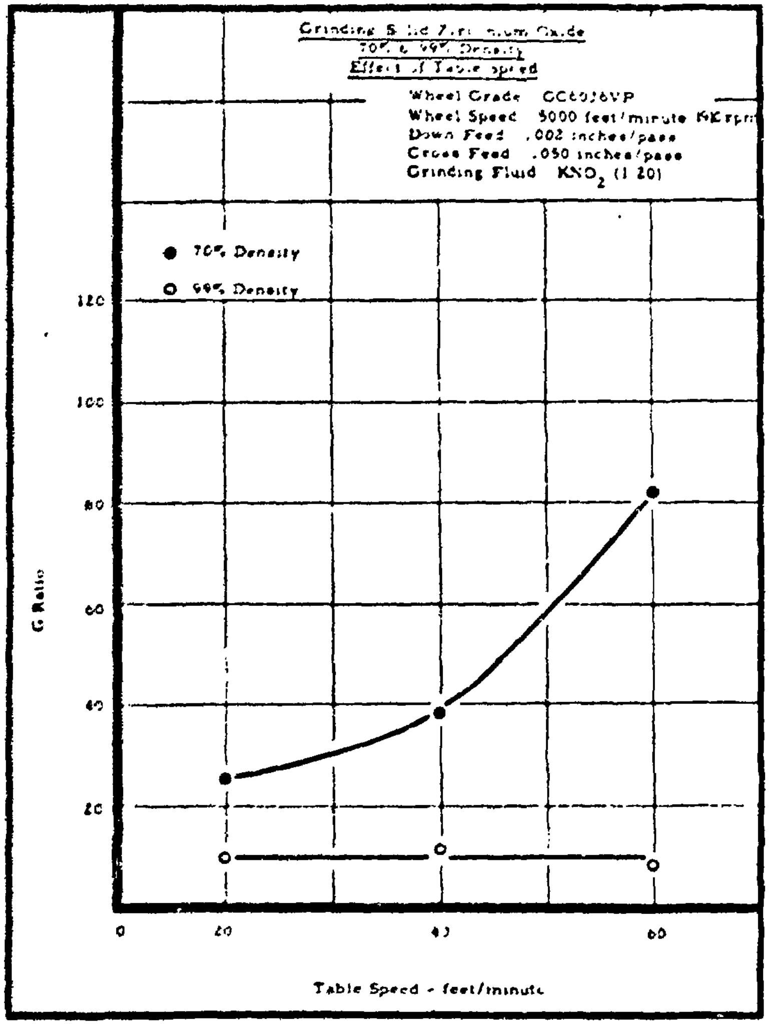
See Text page 277

Figure 335



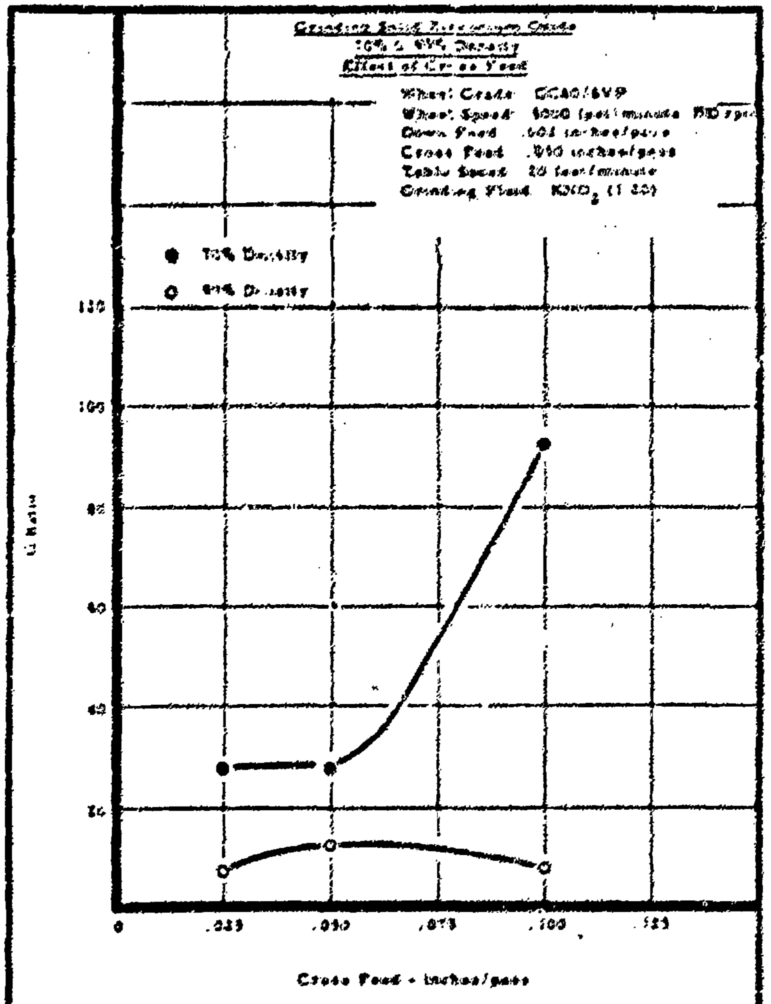
See Text page 277

Figure 336

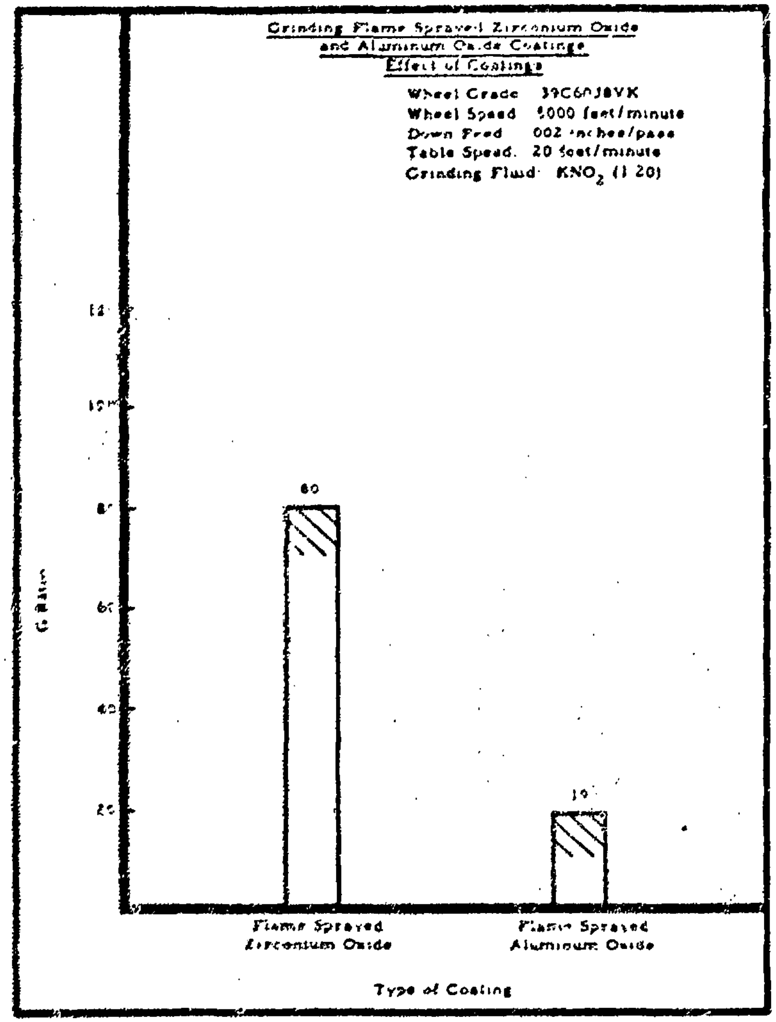


See Text page 277

Figure 337



See Text page 278 | Figure 338



See Text page 278 | Figure 339

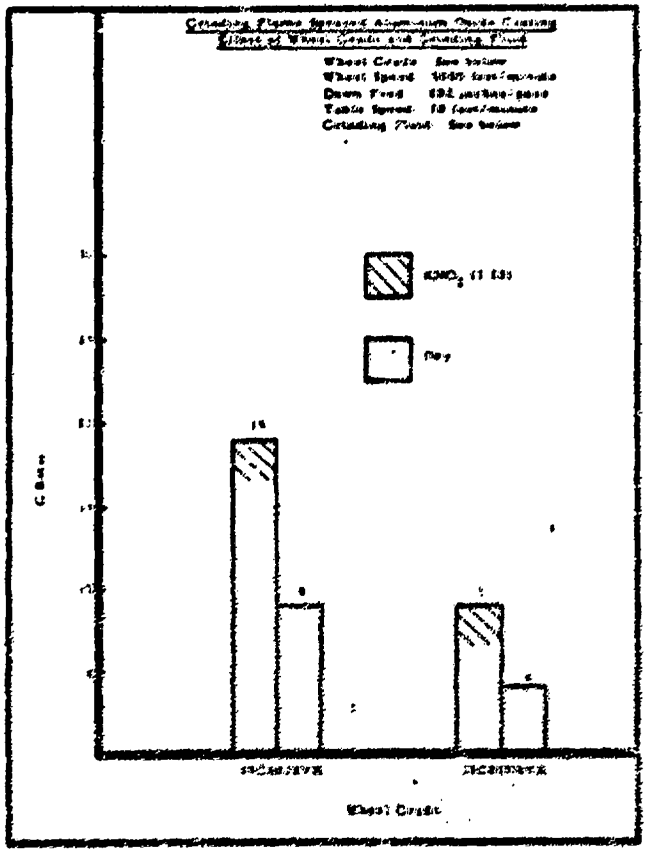


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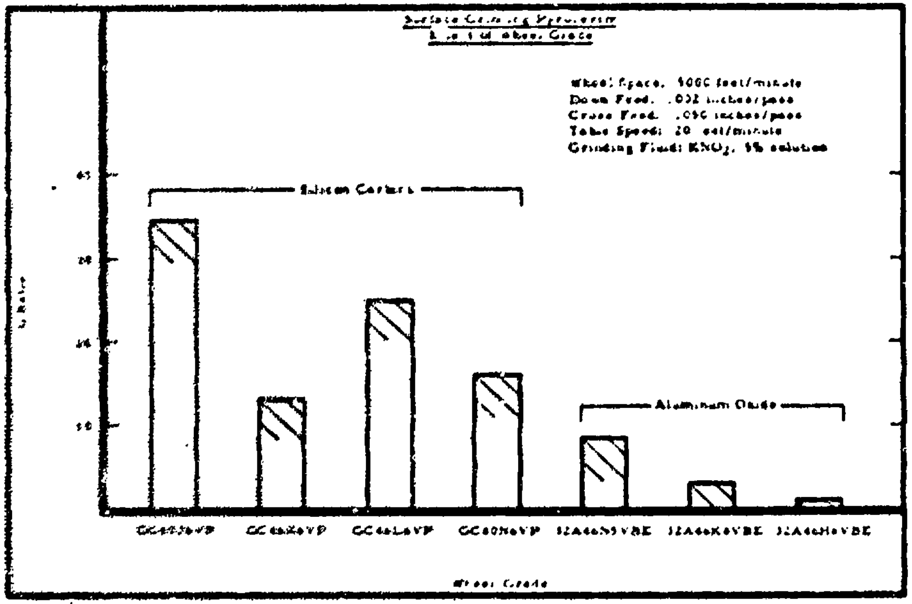
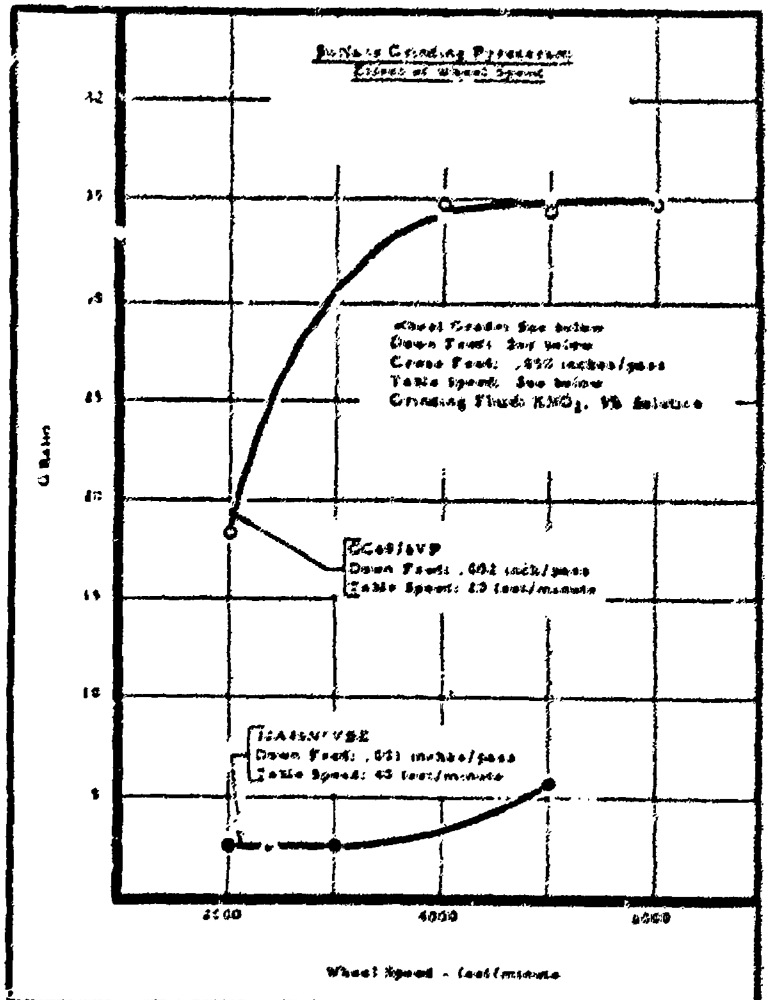
Figure 340



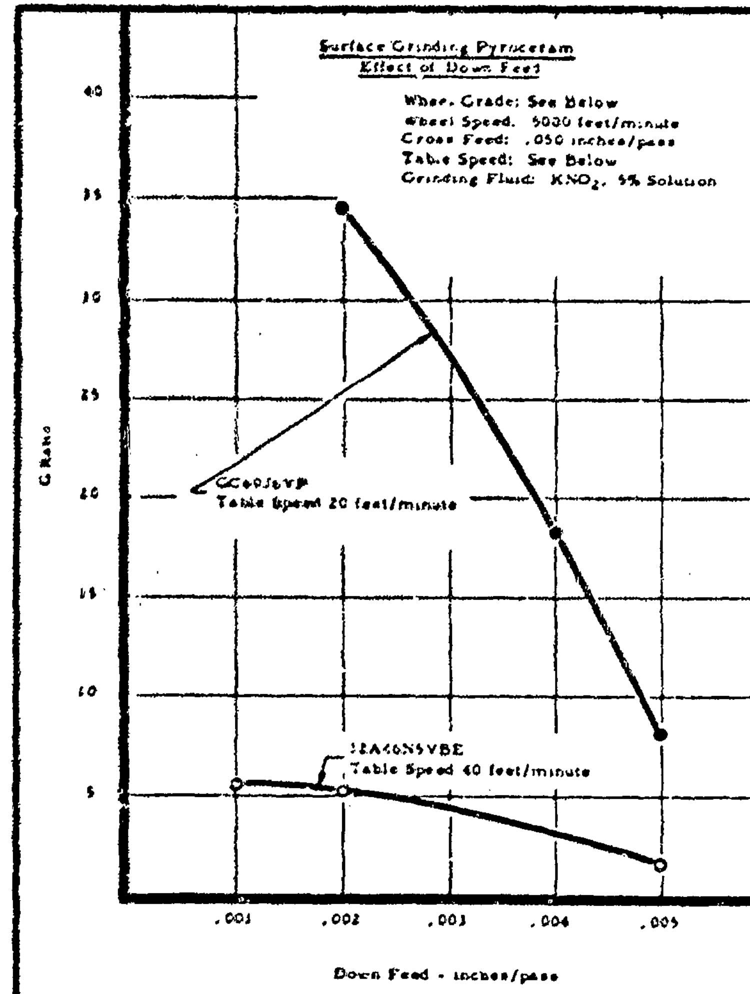
See Text page 278

Figure 341



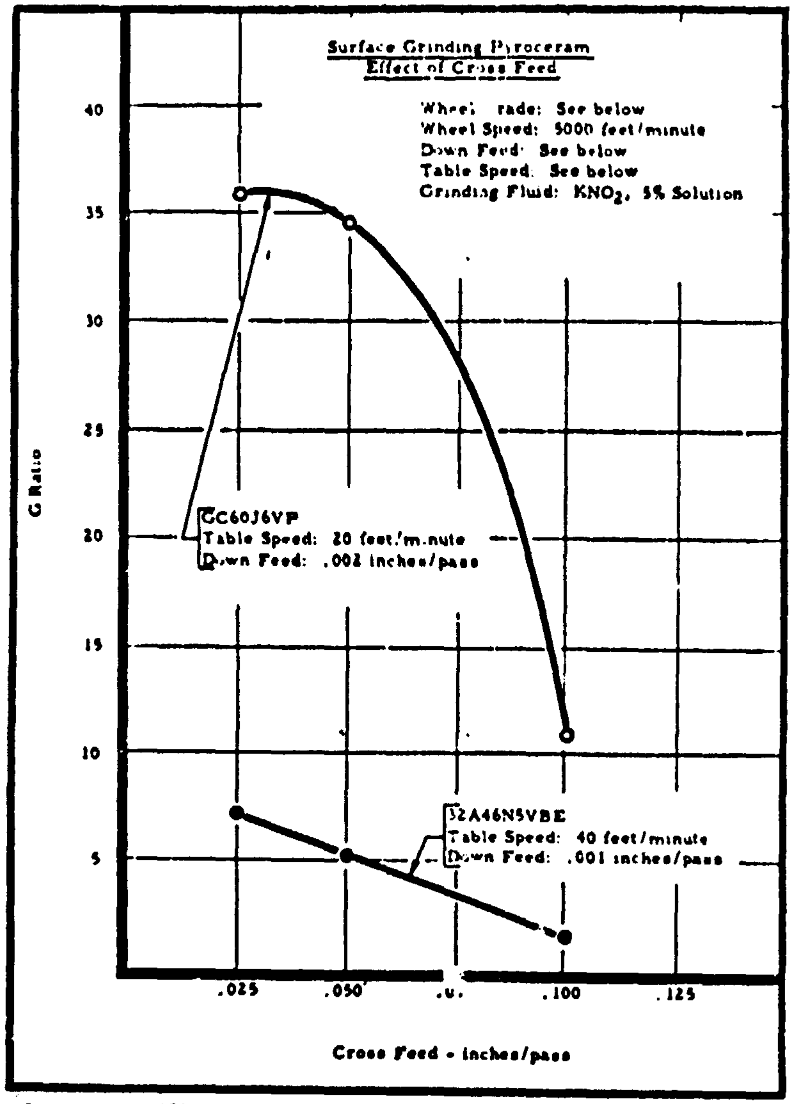
See text, page 279

Figure 342



See text, page 279

Figure 343



See text, page 279

Figure 344

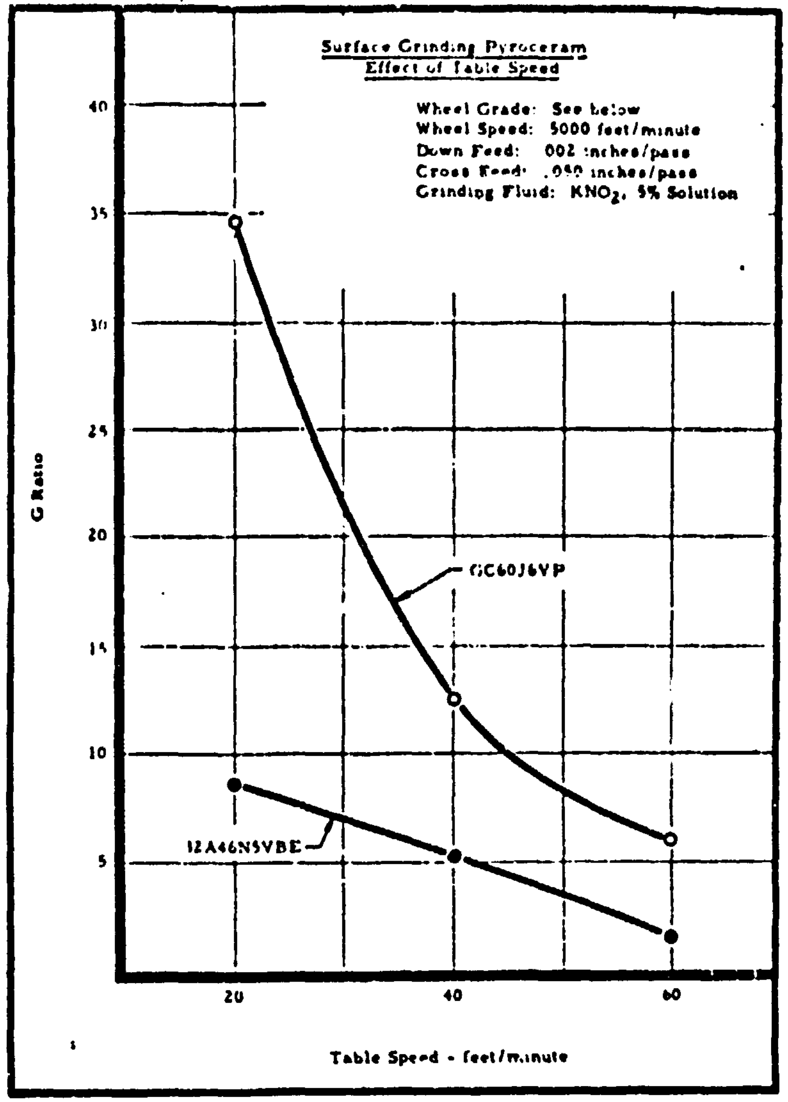


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Figure 345

XIV. EVALUATION OF TORNETIC DRILLING AND TAPPING UNITS

A program was set up to determine the relative drilling and tapping characteristics of a Tornetic unit versus that of a conventional drill press. It should be pointed out that in drilling with the conventional drill press the speed and feed remain constant during the drilling operation. Lifewise, in conventional tapping on a drill press, the speed remains constant.

The design of the Tornetic system is based on the principle that all materials yield to a cutting tool at some specific speed and feed and that this yield will vary in a single material during a single operation with the same cutting tool as the cutting edge becomes dull.

The Tornetic units are equipped with D.C. drive motors in which the maximum torque output and speed can be adjusted by means of a control box, known as a "computer". By limiting the maximum torque available at the spindle, the torque can be set so that the spindle will stop rotating before the drill or tap breaks.

Drilling

The Tornetic drilling unit, Model DM 200D-10, with the computer along side of it is pictured in Figure 346, page 295. This unit has a drilling capacity to 3/4 inch. A drill dynamometer, shown in the picture on the table of the drill press, was used to calibrate the dial settings on the computer for various speeds in terms of available torque at the spindle.

The feed mechanism on the Tornetic drill press is operated by means of air pressure which acts against an oil column. The flow of oil to the feed cylinder is regulated by an adjustable valve. Thus, the maximum feed rate is determined by this valve setting. However, the actual feed rate is determined by the air pressure, the flow valve setting and the resistance the drill encounters in drilling the hole.

The Tornetic drill press thus provides variable feed, cutting speed and torque at the spindle. An electric generator type tachometer was installed to continuously indicate actual rpm of the spindle. In addition, a mechanical type indicator was attached to the quill to determine actual feed rates. While recommendations are given in the instruction book regarding air pressure and pulley arrangement for various drill sizes, the final setting of the various controls is left to the judgment of the operator to obtain optimum conditions.

The object of the drilling tests on the Tornetic unit was to compare the results with those obtained under identical conditions uitlizing conventional machine tools. A Cincinnati 16" box column drilling machine was used for comparison purposes. This machine is equipped with an infinitely variable feed and speed drive.

Drilling (continued)

Operating characteristics of the Tornetic drilling unit are shown in Figures 347 through 350, pages 296 and 297. The relationships between the stalling torque (maximum available torque) at the spindle for various torque settings on the computer are presented in Figure 347, page 296. There was a rapid rise in the magnitude of the stalling torque as the torque setting was increased with the motor-spindle ratio of 1:0.23 and practically no increase at the ratio of 1:4.3. Note that for the ratio 1:0.23, the stalling torque actually decreased when the torque setting was increased beyond a torque setting of 40 on the computer. It should also be pointed out that the relationship between the computer torque setting and the stalling torque is not linear.

An additional set of curves is presented in Figure 348, page 296, showing the spindle speed for each speed setting on the computer for a motor-spindle ratio of 1:0.83. As indicated in the chart, a different relationship exists for each torque dial setting.

The thrust force on the drill for various air pressures is shown in Figure 349, page 297. The curve indicates that a linear relationship exists between the air pressure and the thrust force. At the maximum air pressure of 100 psi, a thrust force of 460 lbs. is available on the drill.

The curve in Figure 350, page 297, shows the range of feeds in inches per revolution for various thrust forces while drilling with a 1/4" diameter drill. The flow rate valve had been adjusted so as to obtain a feed of .001 in./rev. at an air pressure of 50 psi in a B-120VCA titanium alloy, 400 BHN. Without changing the flow valve, the air pressure was changed over its full range of zero to 100 psi, and the feed was measured. The lower curve in the chart represents the feeds while actually drilling the B-120VCA titanium alloy with a 1/4" diameter drill, while the upper curve represents the rate of advance of the drill as it approaches the workpiece before it starts drilling.

Drilling Pressed and Sintered Tungsten, 96% Density, 34 R_c

Figure 351, page 298, shows a comparison of the drill life results on the Tornetic unit with that on a conventional drill press. Carbide drills were used in all of the tests since high speed steel will not drill unalloyed tungsten.

The tungsten is extremely difficult to drill and tool wear occurs very rapidly. The maximum drill life obtained on the conventional machine was four holes at a drill speed of 150 feet/minute and a feed of .002 in/rev. The drill life on the Tornetic unit was less because the maximum available torque was insufficient to continue to rotate the drill after it became partially dull. Hence, at drilling speeds of 150 and 200 feet/minute, it was necessary to remove the drill after the first hole was about 90% through because the machine stalled.

Drilling Pressed and Sintered Tungsten, 96% Density, 34 R_c (continued)

At a drilling speed of 100 feet/minute, the drill life was two holes on both the Tornetic unit and the conventional machine tool. On Tornetic unit, at a still lower speed of 75 feet/minute, the chisel edge of the drill wore to the point where the maximum thrust force available, 465 lbs., was not enough, and the unit stopped feeding after two holes were drilled.

Drilling D-31 Columbium Alloy, 225 BHN

The results obtained on the D-31 columbium alloy, 225 BHN, are shown in Figure 352, page 298. At a cutting speed of 100 feet/minute 150 holes were obtained on the conventional drill press, while 124 holes were obtained on the Tornetic unit. On Tornetic unit as the drill became dull, the cutting speed had decreased 10%. At the drilling speed of 150 feet/minute, the torque was not sufficient to drill the columbium alloy; hence, the unit stalled. Note that the drill size was .150" diameter (#21).

Drilling TZM Molybdenum alloy, 299 BHN

In the drilling tests previously conducted on the TZM molybdenum alloy, 229 BHN, 1/4" diameter drills were used. The same size drill was used on the Tornetic unit. However, as noted in Figure 353, page 299, the required torque was not available at the cutting speeds of 100, 125 and 150 feet/minute used on the conventional drill press. At a lower speed, 75 feet/minute, 100 holes were drilled with only .010" wearland on the drill. The test was discontinued at this point since the speed was below that used on the conventional machine.

Drilling 90 Tantalum - 10 Tungsten Alloy, 207 BHN

In drilling the 90 tantalum - 10 tungsten alloy, 207 BHN, the drill life was appreciably longer with the Tornetic unit at the higher speeds, see Figure 354, page 299. At the recommended drill speed of 50 feet/minute, the drill life was 43 holes on the conventional drill press and 38 holes on the Tornetic unit. However, at a drill speed of 60 feet/minute, 24 holes were obtained on the Tornetic unit and only eight holes on the conventional drill press.

Drilling B-120VCA Titanium Solution Treated and Aged to 400 BHN

Figures 355 and 356, page 300, show the drill life results and change in feed rate when drilling B-120VCA titanium aged to 400 BHN with a conventional drill press and the Tornetic drill unit. At a drilling speed of 20 feet/minute and a feed of .002 in./rev., the conventional drill press provided a drill life of 77 holes, see Figure 355, page 300. The Tornetic drill press was set up for the same initial drilling conditions, and a drill life of 97 holes was obtained. However, with the conventional machine, the feed was constant at

Drilling B-120VCA Titanium Solution Treated and Aged to 400 BHN (continued)

.002 in./rev. throughout the tests; while, with the Tornetic unit, the feed automatically decreased somewhat uniformly from .002 in./rev. at the start to .0008 in./rev. on the 97th hole.

When the feed was reduced to .001 in./rev. at a cutting speed of 20 feet/min., the constant feed drill press provided a drill life of 72 holes, while the Tornetic unit provided a drill life of 84 holes. In this test, the feed decreased from .001 in./rev. to .0005 in./rev.

The data in Figure 355 has been replotted in Figure 356, page 300, in terms of production rate instead of feed. It is apparent from this chart that at a feed of .002 in./rev., where the Tornetic unit produced 30% more holes per tool, the production rate was appreciable less because the feed automatically decreased as the drill became dull.

Drilling Rene 41 Solution Treated and Aged to 370 BHN

The data shown in Figure 357 page 301, shows that with the conventional drill press operating at 20 feet/minute with a feed of .002 in./rev., a drill life of 35 holes was obtained. With the Tornetic unit operating initially at this condition, drill life increased to 39 holes. However, while the initial feed was .002 in./rev., it decreased gradually to about .0007 in./rev. on the 39th hole so that the production rate was 25% less per hole than with the conventional machine.

At a cutting speed of 25 feet/minute and a feed of .002 in./rev., the drill life on the Tornetic unit was 35 holes as compared to nine holes on the conventional machine, but again the production rate was appreciably less on the Tornetic unit.

Drilling D6AC Steel Quenched and Tempered to 54-58 Rc

Carbide drills were required to drill the D6AC steel quenched and tempered in the hardness range of 54-58 R_c on both types of drill presses. A reasonable drill life was obtained with carbide drills on this steel at a cutting speed of 100 feet/minute and a feed of .001 in./rev. with a conventional drill press. A comparison was then made on the Tornetic drill press under the identical machining conditions, see Figure 358, page 301. Note that on the D6AC steel at each of the three hardness levels, 54, 56 and 58 R_c, the drill life was about 20% less on the Tornetic unit.

Drilling AISI 4340 Steel Quenched and Tempered to 52 R_c

The Tornetic unit showed a definite advantage over the conventional drill press in drilling the AISI 4340 quenched and tempered to 52 R_c, see Figure

359, page 302. At a cutting speed of 30 feet/minute and a feed of .001 in./rev., the drill life with the conventional drill press was 37 holes, while the Tornetic unit provided a drill life of 56 holes. The unit stopped feeding on the 57th hole because the drill was dull. The difference in the production rate with the two units was small.

Drilling 6Al-4V Titanium Alloy Solution Treated and Aged to 360 BHN

A comparison of the tool life results in drilling the 6Al-4V titanium alloy solution treated and aged to 360 BHN is presented in Figure 360, page 302. The tool life was appreciably higher on the conventional drill press at a cutting speed of 65 feet/minute and a feed of .002 in./rev. Also, the wearland on the drill was less with the conventional unit than with the Tornetic unit at a cutting speed of 50 feet/minute after 100 holes were drilled.

In the drilling of the difficult to machine alloys investigated in this program, it is very important that the required speeds and feeds be used. Even slight deviations may result in significant reductions in tool life. Generally, the selection of speeds on most conventional drill presses is not fine enough to provide the required speeds within plus or minus 10%. The drill life may be negligible on some of these alloys if the speed is only 10% too high. Also on the high strength alloys, very light feeds, less than .002 in./rev., are required. Again the minimum feed on conventional drill presses is rarely less than .002 in./rev. Under these conditions, it is often impossible to obtain a reasonable drill life on some of the difficult to machine alloys.

The Tornetic unit provides an infinitely variable range of speeds and feeds so that the optimum conditions can be selected. Also the provision for adjusting the maximum torque available at the tool if properly used can eliminate tool breakage.

In addition, with the hydraulic feed mechanism, the feed rate automatically decreases as the drill wears. On the high strength alloys, this condition results in extending the life of the drill. However, this same condition may be detrimental in the drilling of work hardenable alloys such as the heat resistant alloys. The Tornetic unit provides a versatile means of obtaining the required machining conditions.

Tapping

The Tornetic tapping unit shown in Figure 361, page 303, was a Model DM 200T with a capacity to 3/4" tap. The unit is equipped with a torque control to

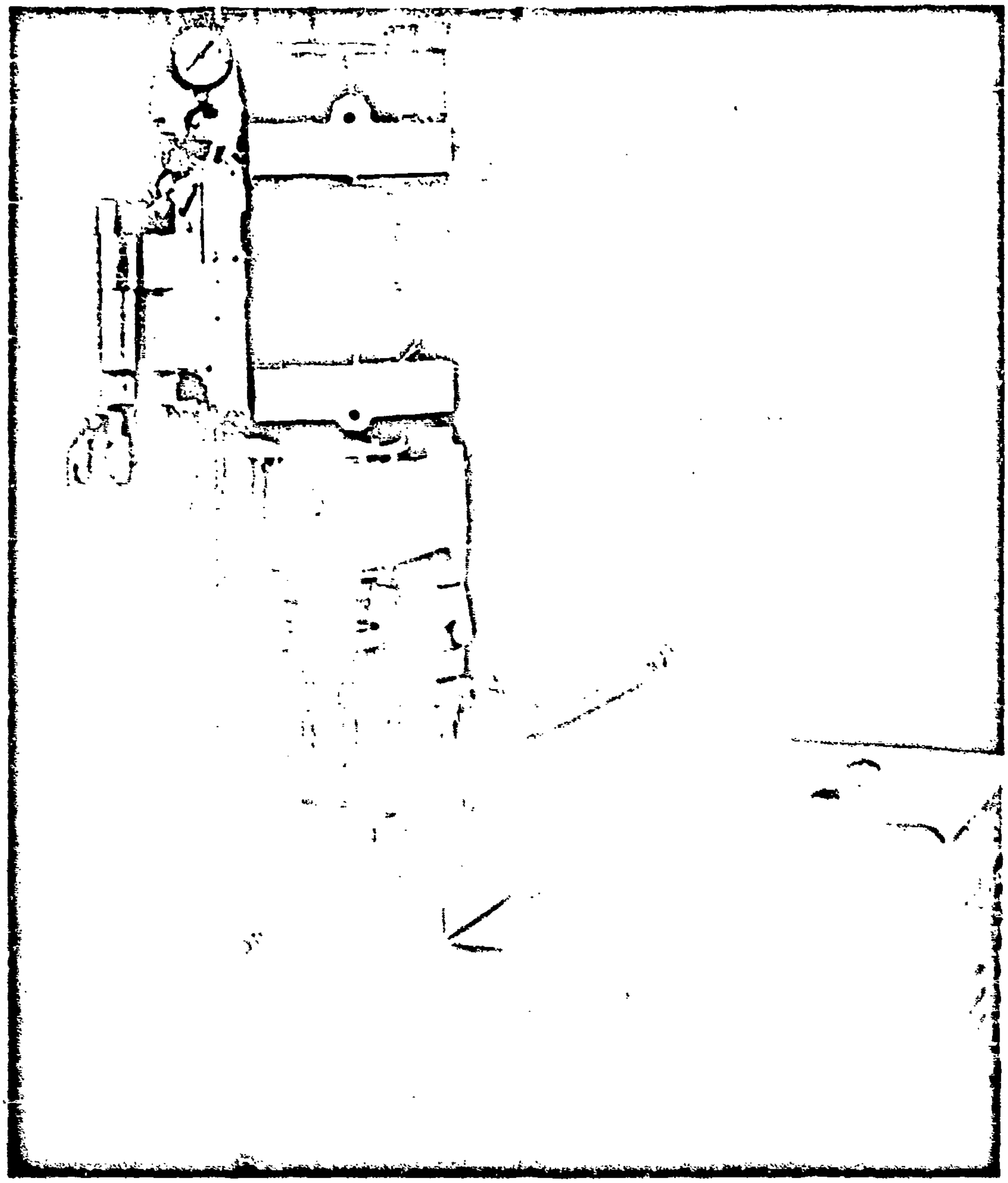
adjust the maximum torque delivered to the spindle, a speed control and a cycling device which reverses the tap periodically during tapping to break up the chips. The controls are shown on the computer box along side of the tapping unit in Figure 361, page 303.

The relationships between the maximum torque available at the spindle (stalling torque) and the torque computer setting for several motor to spindle pulley ratios are presented in Figure 362, page 304. The maximum torque available at the ratio 1:0.24 was 260 inch-pounds. However, for the ratio of 1:0.08 the stalling torque was above 350 inch-pounds. The spindle speed depended not only on the speed computer setting, but also on the torque computer setting as is shown in Figure 363, page 304. An almost linear relationship exists between spindle speed and speed computer setting at a torque setting of 100.

A comparison of tap life on a conventional tapping unit and a Tornetic unit is shown in Table 20, page 305, for tapping the various refractory alloys, B-120VCA titanium 400 BHN, Rene 41 and D6AC 54 R_c. Since tapping data was already available from earlier tests on a conventional unit for a 5/16-24 NF tap size for all of the materials except the D-31 columbium alloy, this same tap size was used on the Tornetic unit. A 1/4-28 NF tap had been used on the D-31 columbium alloy so this tap size was used on the Tornetic unit on this alloy.

A Class 2 go-no-go plug gage was used to check the threads during the tests. In every test on the conventional machine the tap broke before the thread was out of gage limits. On the Tornetic unit the spindle stalled after a wearland developed. The Tornetic unit was always set for maximum torque, but nevertheless the spindle stalled before the hole was completely tapped in many of the tests. Cutting speeds lower than that used on the conventional machine had to be used on the Tornetic unit in order to obtain higher torque. The cycling device did not alleviate the stalling problem. Undoubtedly, additional holes could have been tapped on the Tornetic unit if higher torque had been available.

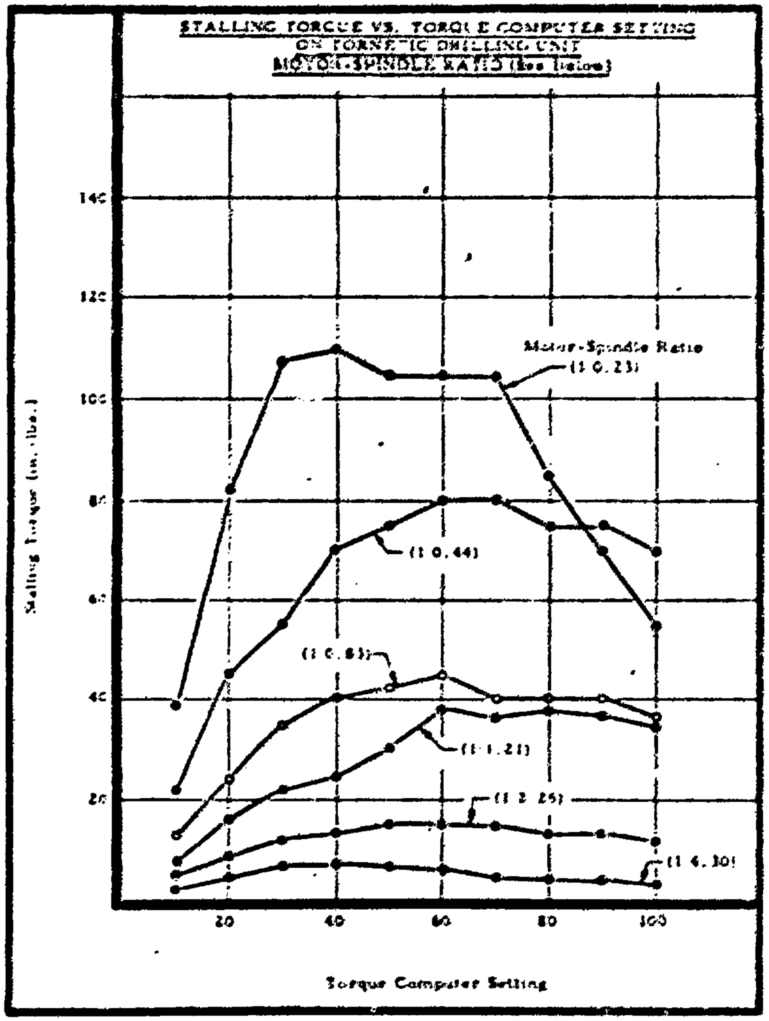
The Tornetic tapping unit has certain advantages over the conventional machine. First, the torque control provides a means of preventing tap breakage; second, the infinitely variable speed permits the selection of the proper speeds; and third, the cycling device breaks up the chips which helps in chip removal. At a given cutting speed, there is no reason why the Tornetic unit would not provide at least the same tap life that was obtained on the conventional machine.



Tornetic drilling unit with computer. The unit was purchased as shown with the exception of the drill dynamometer clamped to the base. An electric generator tachometer and a feed measuring device (not shown) have been added to the unit.

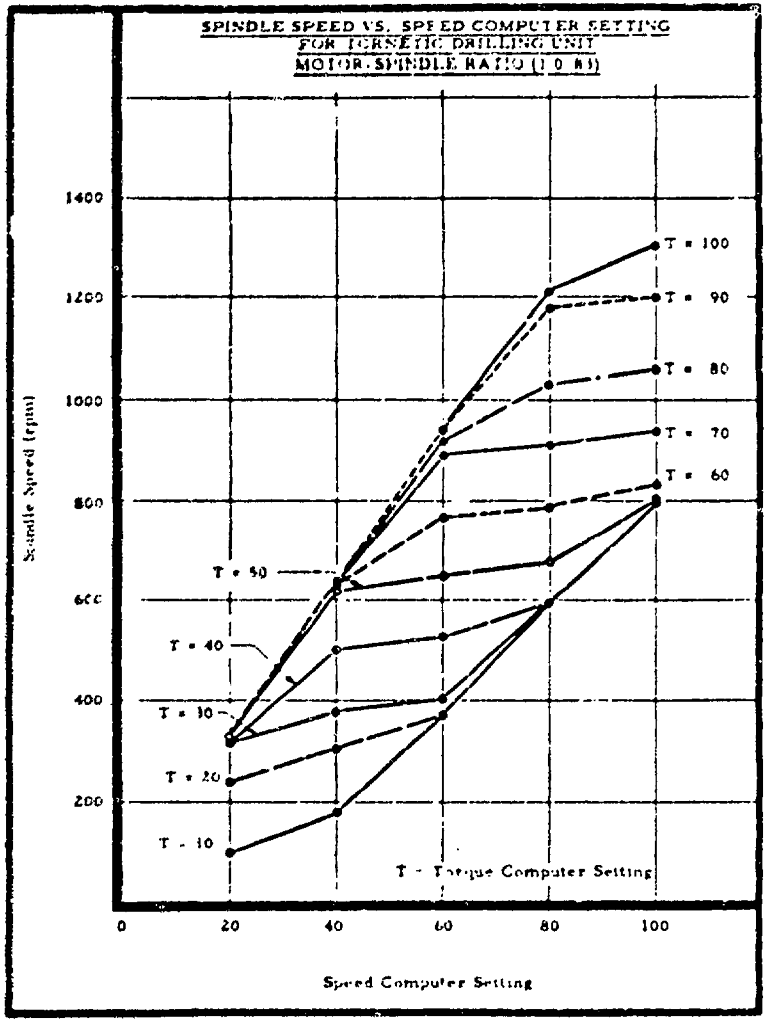
Figure 346

See Text, page 289



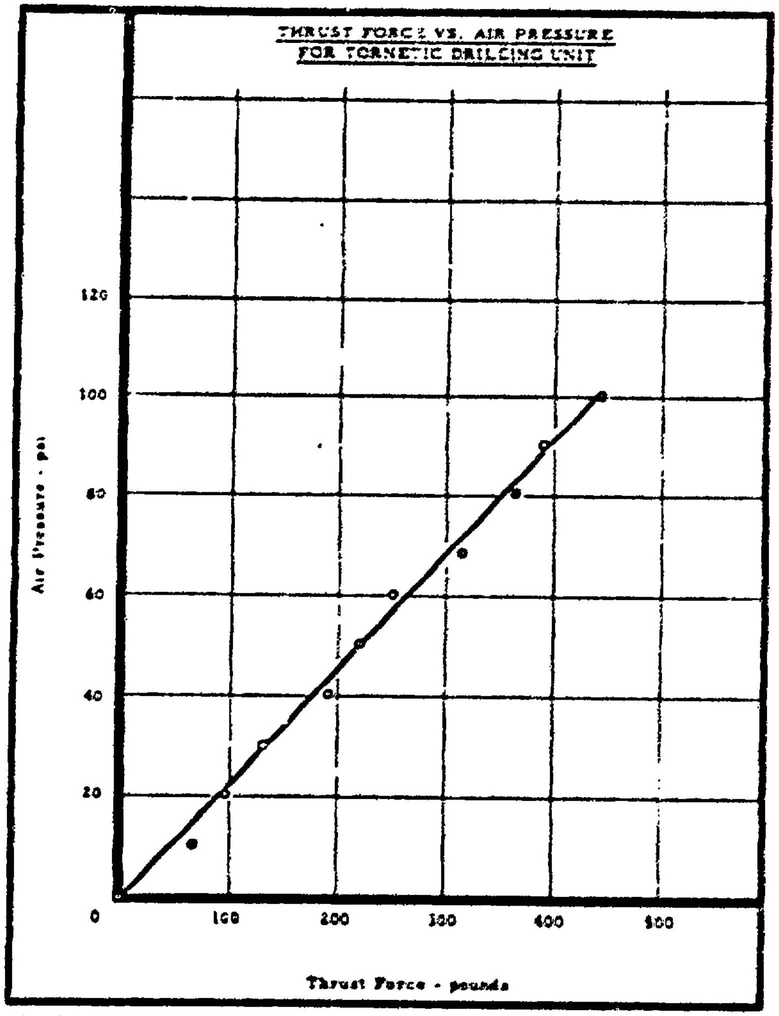
See Text page 290

Figure 347



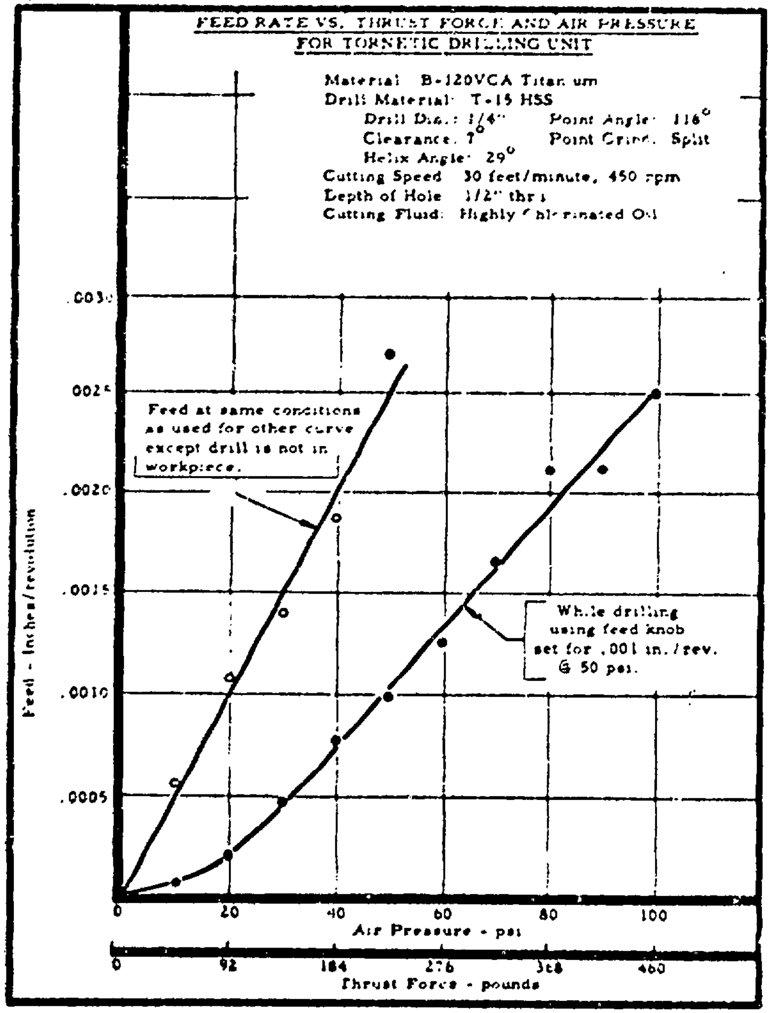
See Text page 290

Figure 348



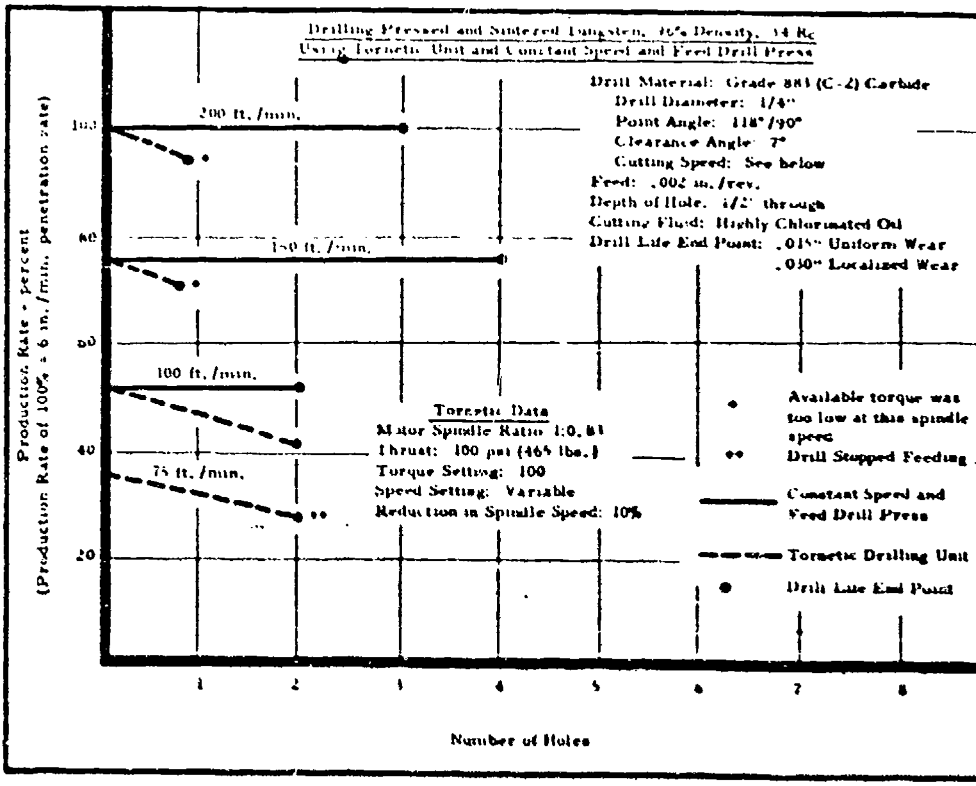
See Text page 290

Figure 349



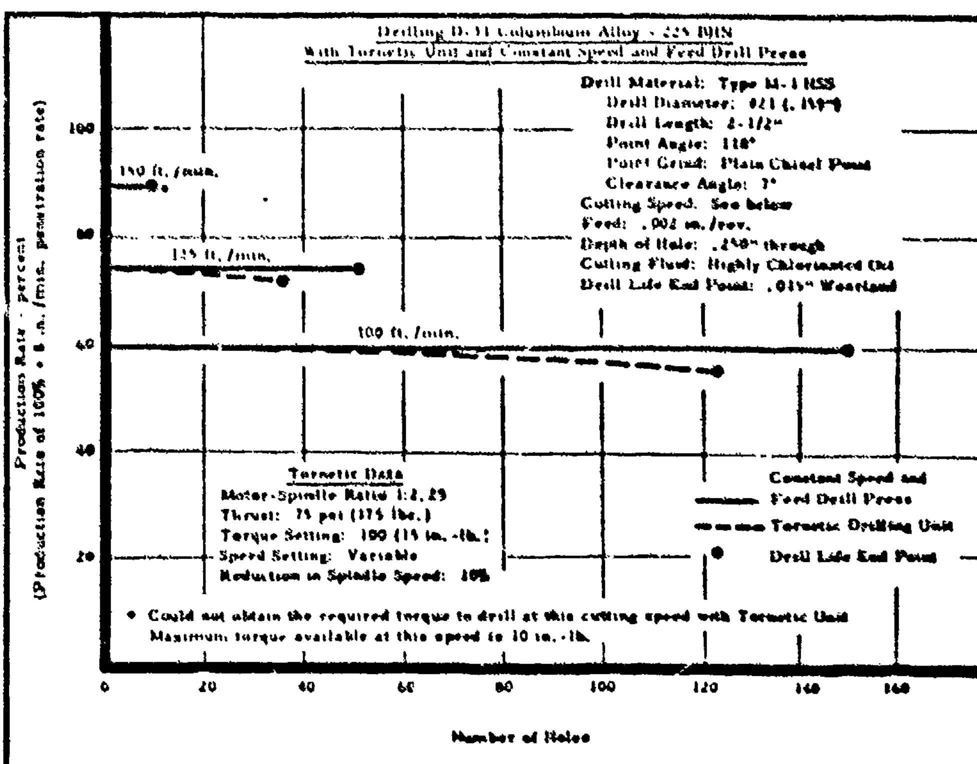
See Text page 290

Figure 350



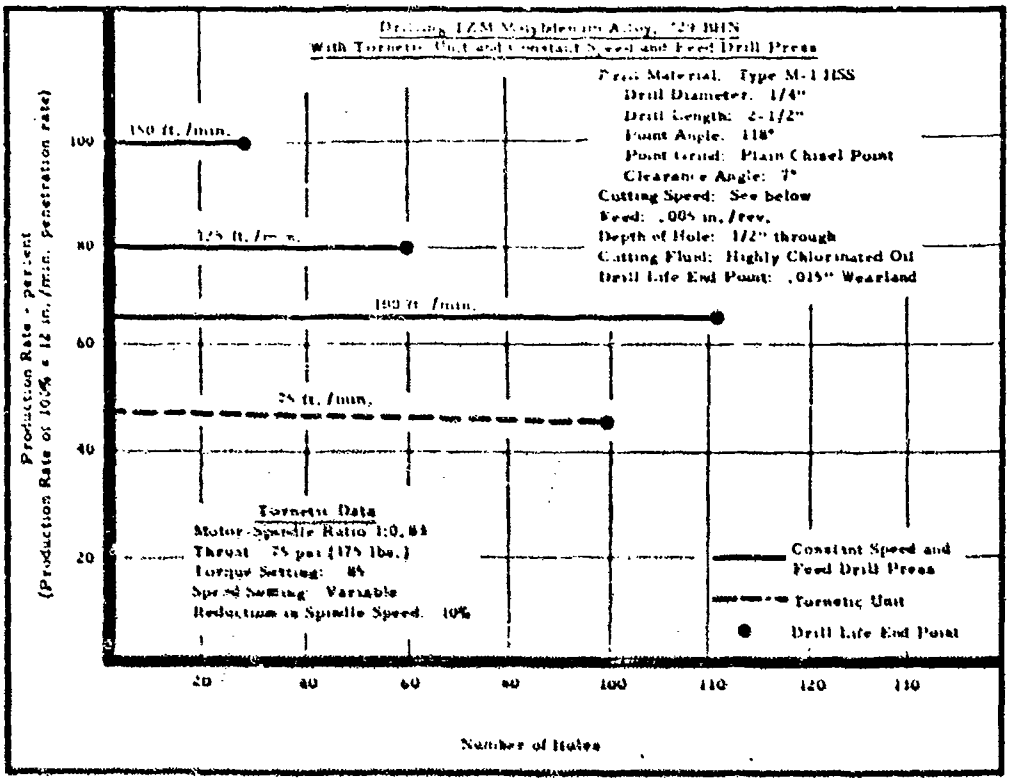
See Text, page 290

Figure 151



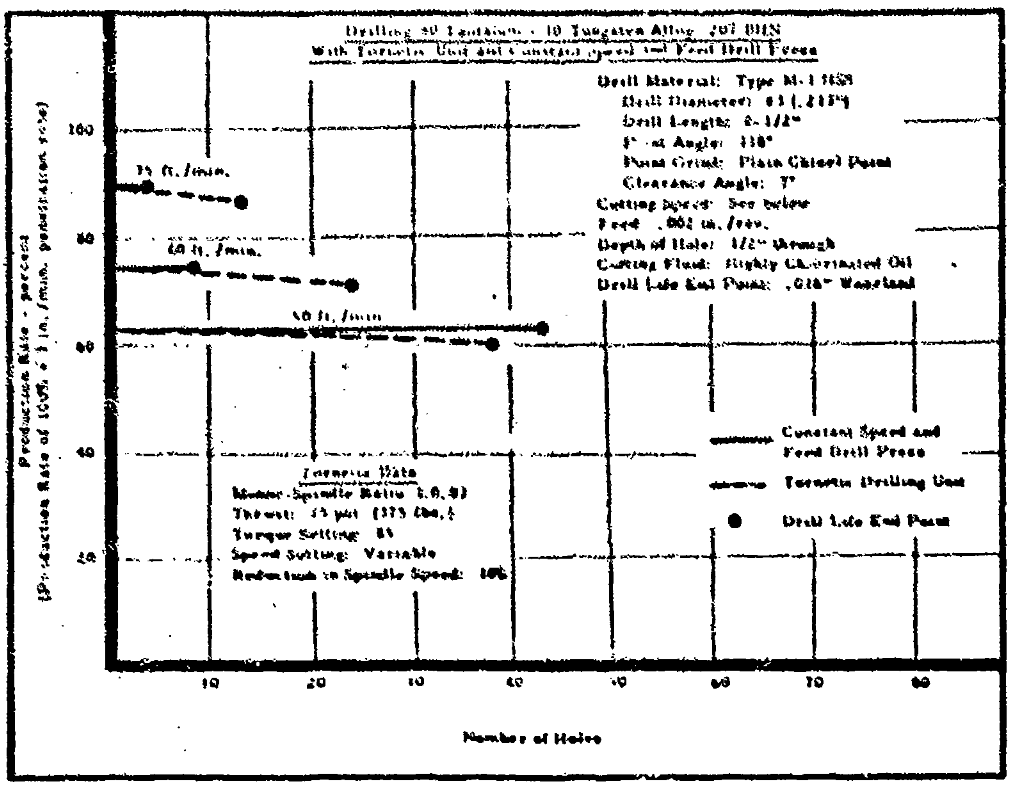
See Text, page 291

Figure 152



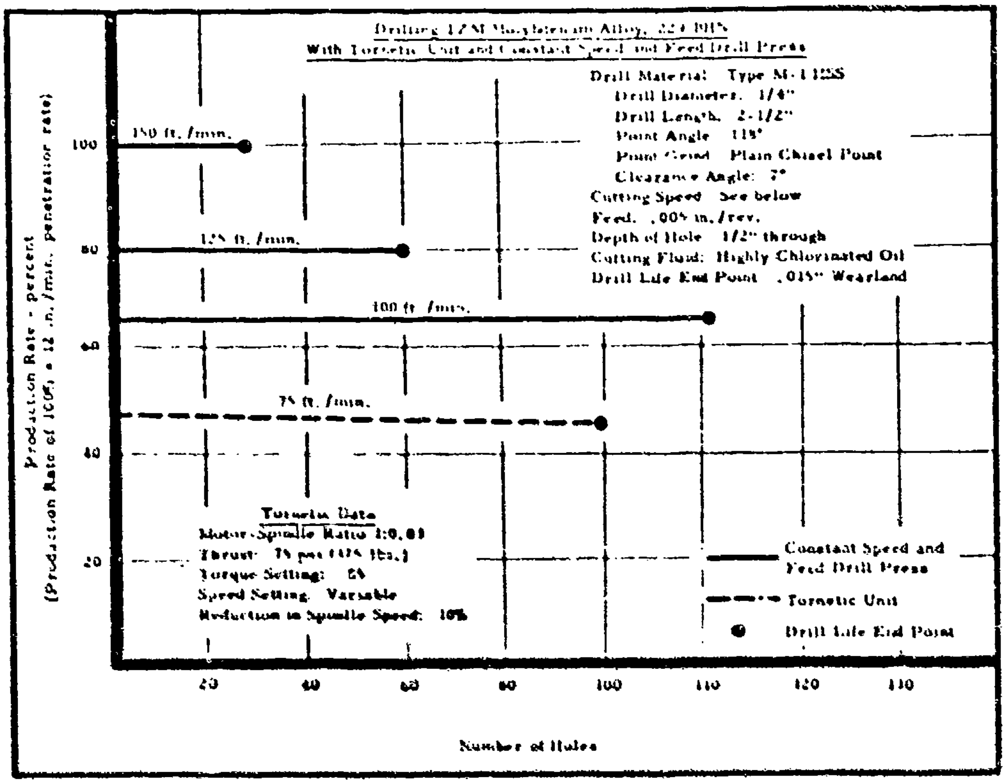
See Text, page 291

Figure 353



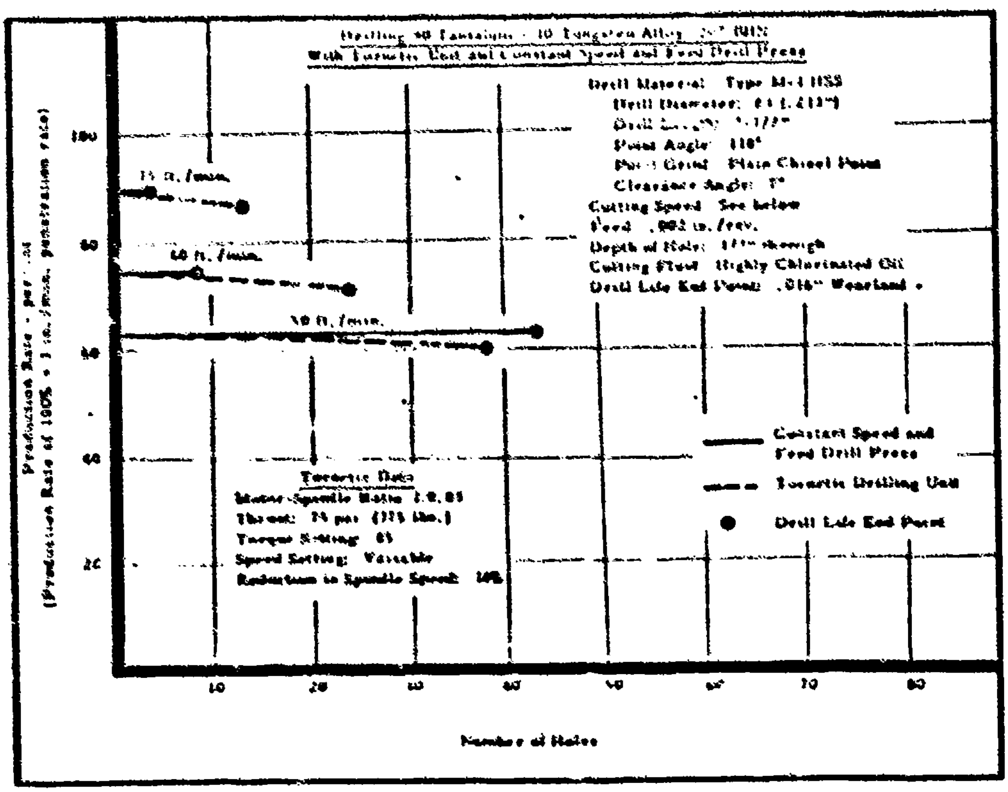
See Text, page 291

Figure 354



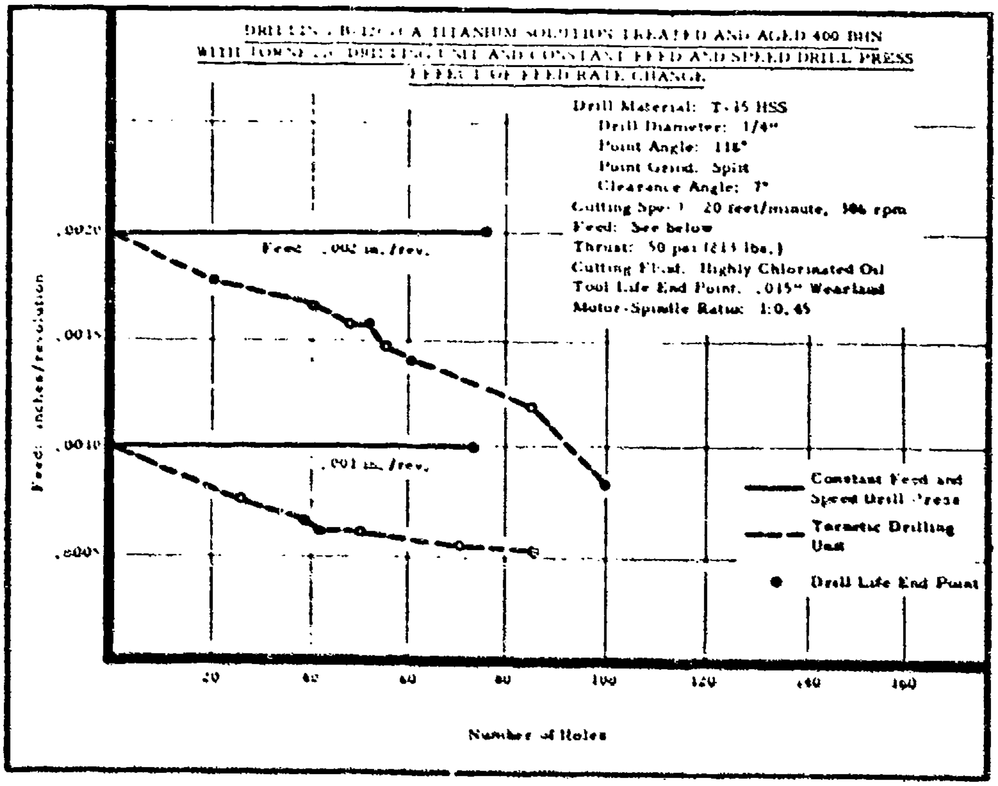
See Text, page 291

Figure 183



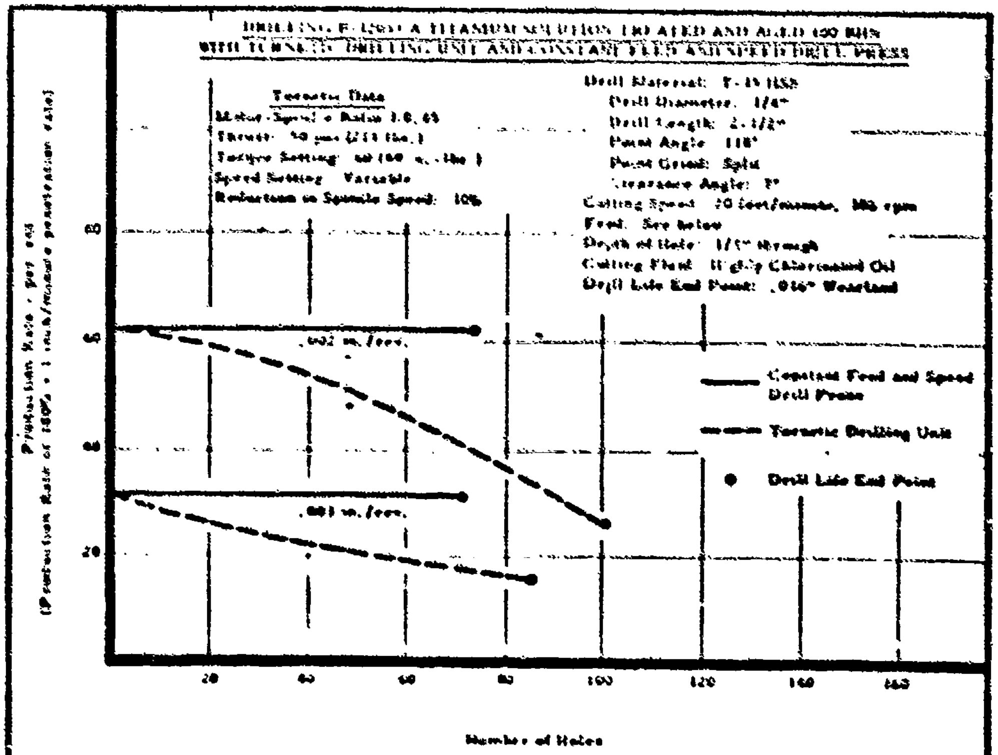
See Text, page 291

Figure 184



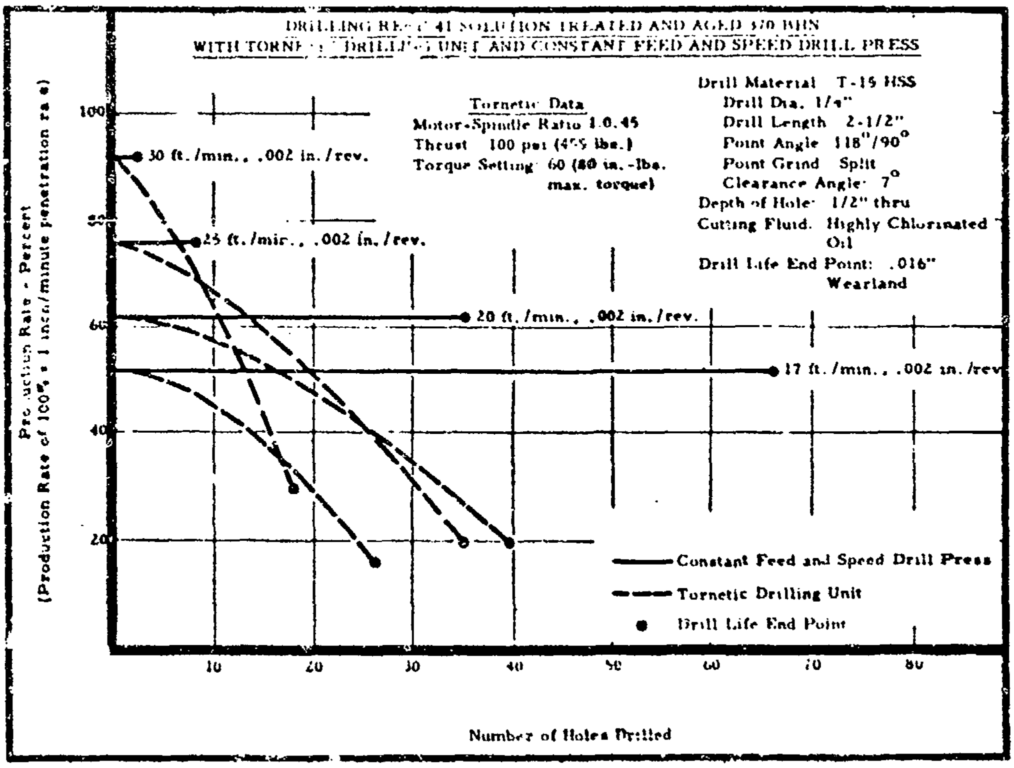
See Text, page 293

Figure 155



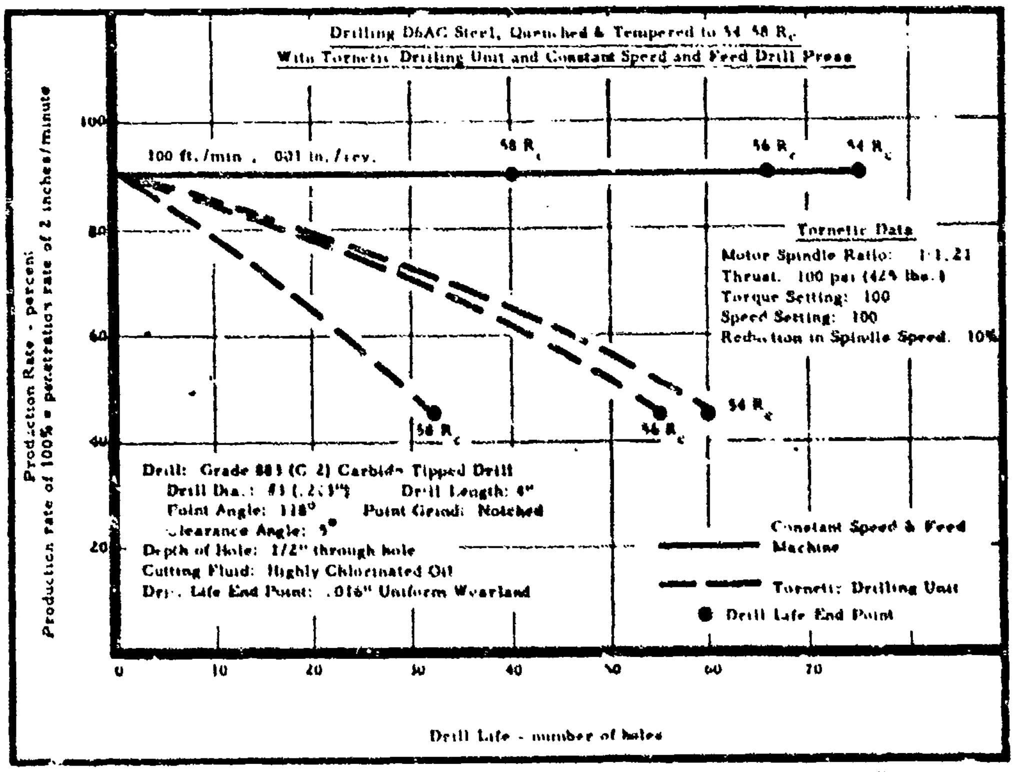
See Text, page 293

Figure 156



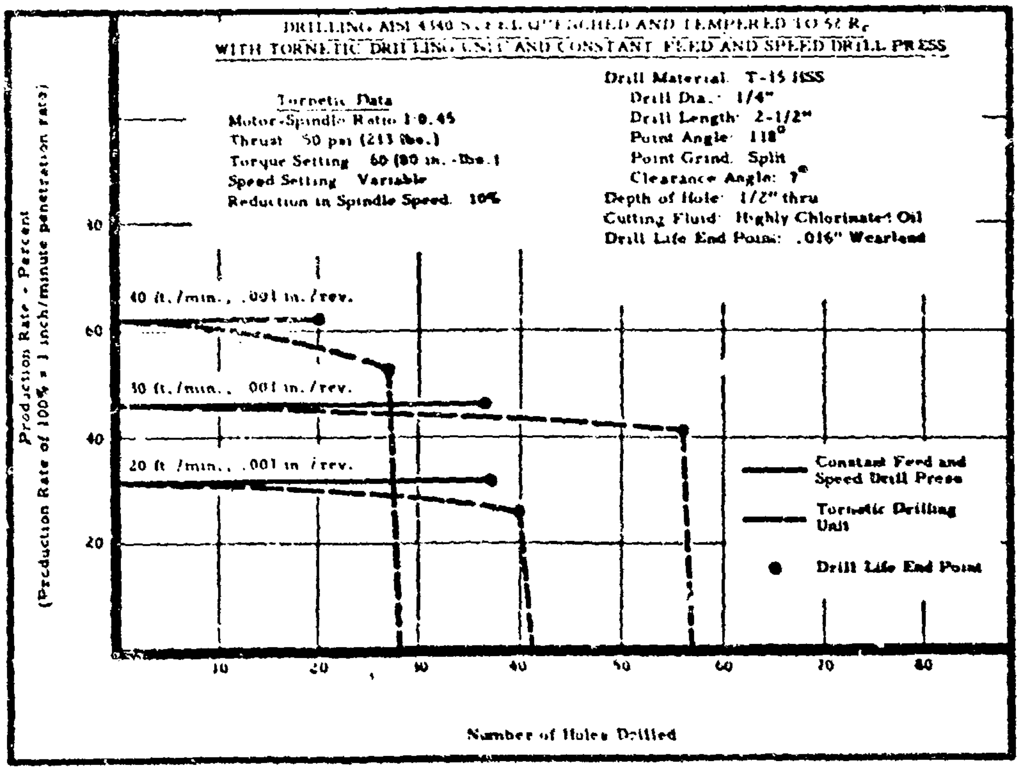
See Text, page 292

Figure 357



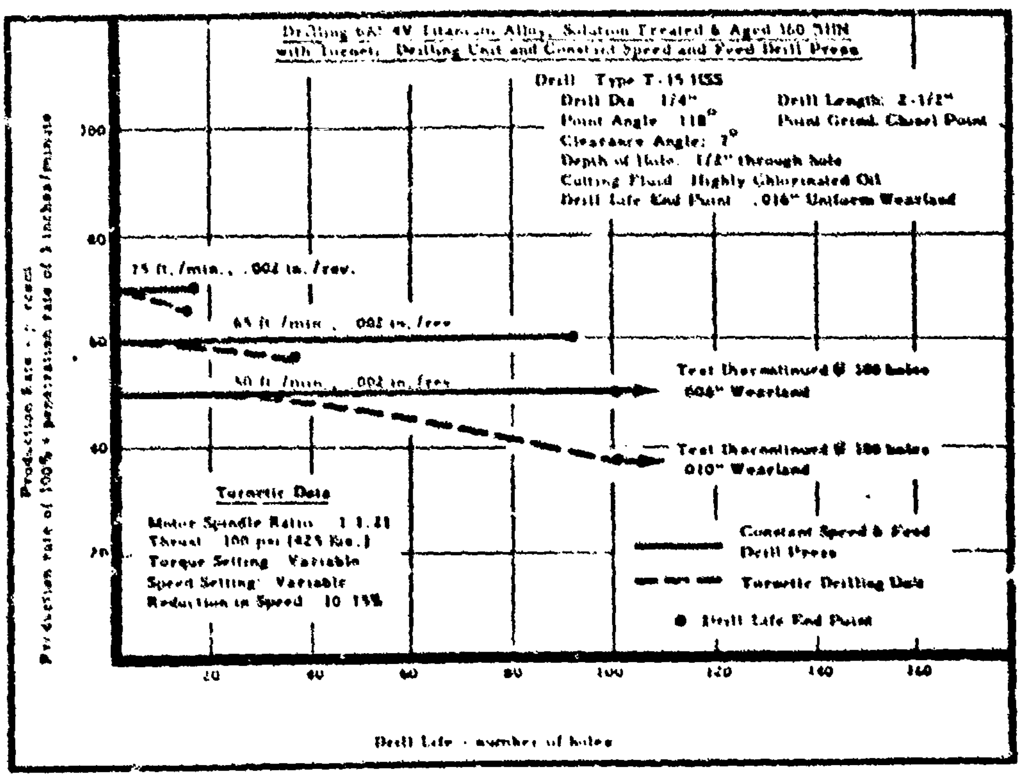
See Text, page 292

Figure 358



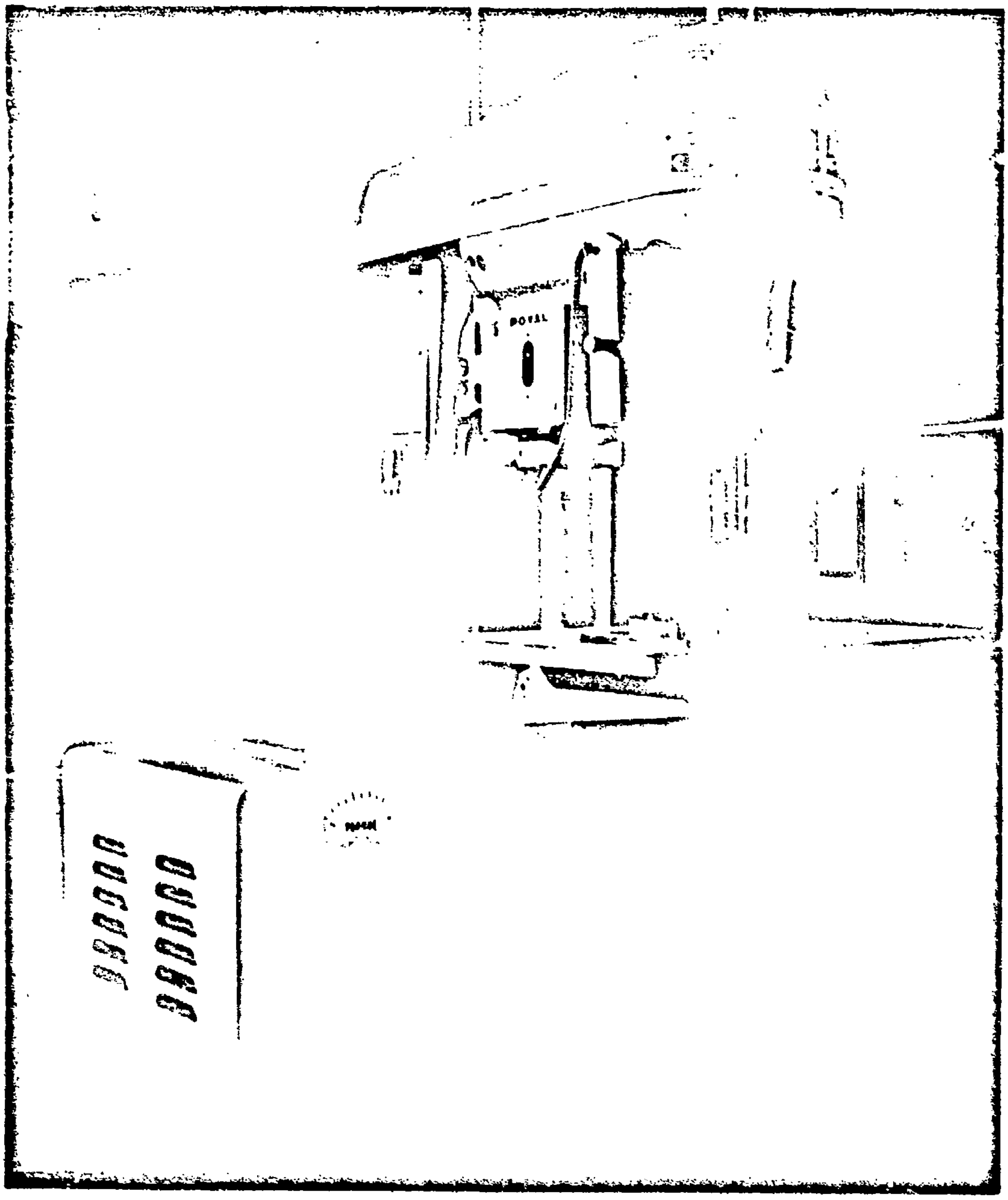
See Text, page 291

Figure 159



See Text, page 291

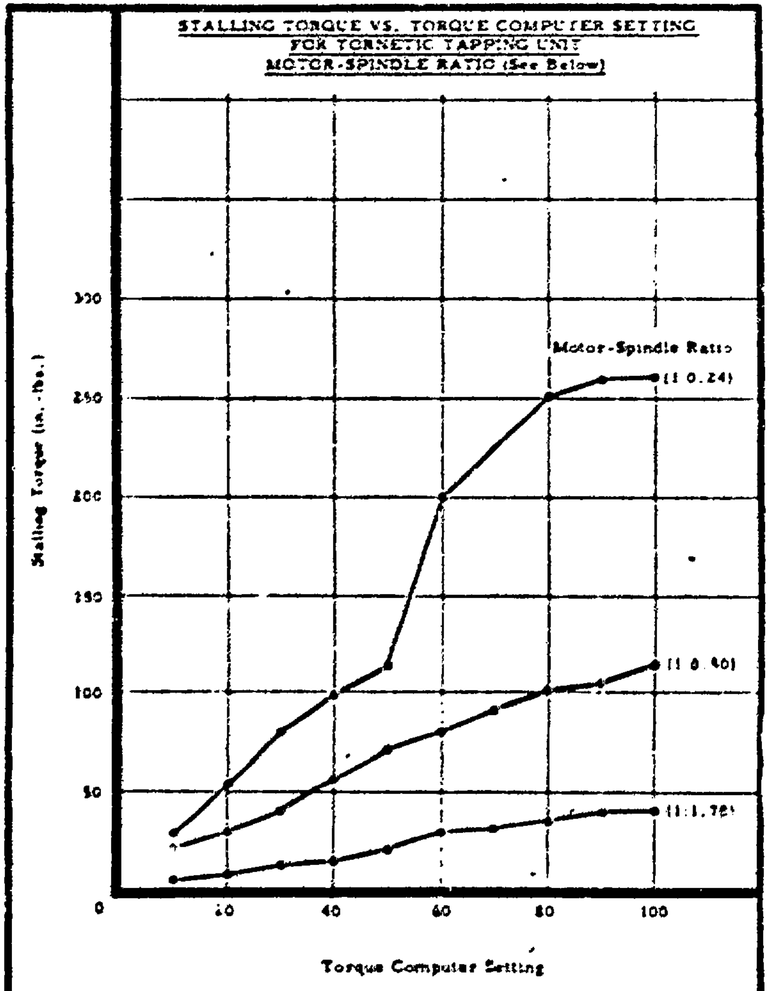
Figure 160



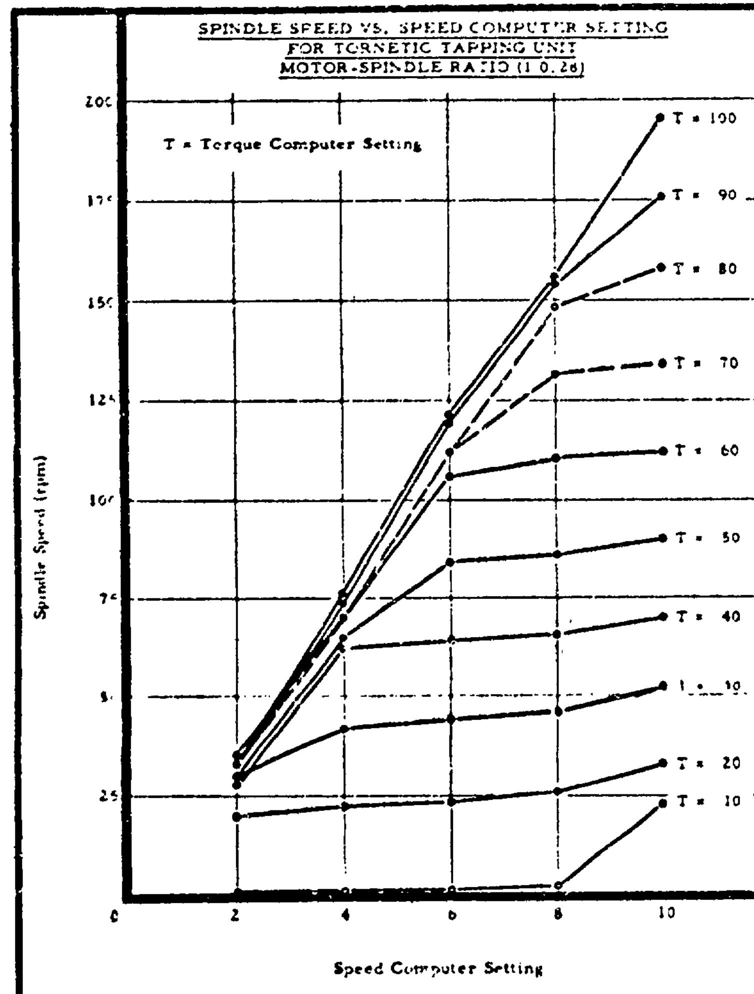
Tornetic tapping unit with computer. The basic machine tool is a 16" drill press not supplied by Dyna Systems Inc., manufacturers of Tornetic systems. Dyna Systems Inc. supplied the computer, a D.C. motor and a limit switch attached to the drill press.

Figure 361

See Text, page 294



See Text page 294 **Figure 362**



See Text page 294 Figure 363

TABLE 20

Comparison of Tap Life for Conventional and Tornetic Tapping Units

Tap Size: 5/16-24NF and 1/4-28NF   Cutting Fluid: Highly Chlorinated Oil

Percent Thread: 75%   Tap Life End Point: Conventional, Tap Breakage
Tornetic, Tap Stalled

Material	Tapping Unit	Cutting Speed feet/minute	Tap Life Number of Holes
Unalloyed Tungsten	Conventional	5	2
	Tornetic	2	2
D-31 Columbium	Conventional	12	50
	Conventional	16	35
	Conventional	25	4
	Tornetic	9	38*
	Tornetic	12	28*
TZM Molybdenum	Conventional	30	100+
	Conventional	70	100+
	Conventional	95	71
	Tornetic	10	38*
	Tornetic	18	14*
	Tornetic	30	2*
90 Ta-10W	Conventional	5	41
	Conventional	12	24
	Conventional	25	9
	Tornetic	4	36*
	Tornetic	5	27*
	Tornetic	10	18*
B-120VCA Titanium Solution Treated and Aged, 400 BHN	Conventional	9	100+
	Conventional	12	50
	Conventional	22	8
	Tornetic	7	70*
	Tornetic	10	52*
	Tornetic	17	9*
Rene 41 Solution Treated and Aged, 365 BHN	Conventional	5	140
	Conventional	9	40
	Conventional	12	9
	Tornetic	5	25*
	Tornetic	10	14*
D6AC Steel Quenched and Tempered, 54 R_c	Conventional	5	16
	Conventional	9	10
	Conventional	12	4
	Tornetic	5	9*
	Tornetic	9	4*

* Tap stalled, exceeded maximum torque available at spindle
Tap life for conventional tapping machine is point at which tap broke.

See Text page 294

Experimental work was done in 1960 by Boeing Airplane Company in Seattle on the high speed edge milling of aerospace sheet materials. The results indicated that a reasonable cutter life could be obtained in the cutting speed range of 500 to 2000 feet/minute.

Cutting conditions similar to those used by Boeing were investigated further to determine the feasibility of the new machining techniques. Normally, the edge trimming operation on high temperature and high strength sheet materials used for aerospace vehicles required very low cutting speeds and feeds.

The results obtained on B-120VCA titanium, PH 15-7 Mo stainless steel, HS-25 and 6Al-4V titanium indicate that these sheet materials can be edge trimmed over 15 times faster than the previous rate.

The sheet materials evaluated in this program were:

1. B-120VCA Titanium annealed and cold rolled 35-36 R_c
2. 6Al-4V Titanium annealed and cold rolled 35-36 R_c
3. HS-25 Alloy annealed 25 R_c
4. PH 15-7 Mo Stainless Steel annealed 90 R_B

The microstructures are shown in Figures 364 and 365, pages 311 and 312.

Machine Tool Setup

A planer was selected for the high speed edge milling operation in order to obtain the required high table speeds and rigidity. Most milling machines have a maximum table speed of 80 in./min. This operation required table speeds ranging from 40 to 400 in./min. A photograph of the 30 inch by 6 foot Gray planer which was used is shown in Figure 366, page 313, with a special high speed milling head. This milling head was designed and built using an infinitely variable speed motor to provide spindle speeds ranging from 150 rpm to 9000 rpm. This machine was modified to provide variable table speeds ranging from 40 in./min. to 400 in./min. This range of table speeds provided feed rates of .005 to .020 in./tooth. A cutting speed range of 500 to 2000 feet/minute was obtained using a 1-1/4" diameter inserted-tooth throwaway type carbide tipped end mill. The sheet material tested in this program was sheared into test panels 2 feet wide by 4 feet long. The test panels were securely held down on the planer table with a special holding fixture.

A view of the milling cutter head and carbide throwaway type end mill holder used for these tests is shown in Figure 367, page 314. Two nozzles with .027" diameter orifices were used to direct liquid CO_2 on the tool and work material. Only one nozzle can be seen in the photograph; the other nozzle is behind the cutter. Soluble oil spray mist was also used.

Machine Tool Setup (continued)

Figure 368, page 315, shows the high speed edge trimming operation with the liquid CO_2 spraying on the workpiece and cutter. Various depths of cut were taken using the peripheral cutting edge of the inserted tooth cutter. Several tests were made with one set of cutters by moving the cutter head up and down to expose an unused portion on the periphery of the insert. The width of the cut is defined as the thickness of the sheet material tested. The depth of the cut was obtained by moving the cutter into the workpiece in a direction perpendicular to the direction of feed.

High Speed Edge Milling B-120VCA Titanium (35 R_c)

The effect of cutting speed using different feeds is shown in Figure 369, page 316, when high speed milling the B-120VCA titanium alloy dry. Maximum tool life, 52 feet, was obtained at a cutting speed of 1000 feet/minute, without a cutting fluid. Tool life decreased when cutting speeds above and below 1000 feet/minute were used. These data are plotted as a function of feed rate in Figure 370, page 316. Maximum tool life was obtained with a feed of .015 in./tooth and a cutting speed of 1000 feet per minute.

Figure 371, page 317, shows the effect of cutting speed and cutting fluid when high speed milling this alloy. The best tool life, 68 feet of work travel, was obtained using a soluble oil spray mist, at a cutting speed of 1000 feet/minute and a feed of .010 in./tooth. Using these same cutting conditions, milling dry, a tool life of 48 feet was obtained, and when using liquid CO_2, tool life decreased to about 25 feet of work travel.

The effect of tool life on various sheet thicknesses over a range of cutting speeds is shown in Figure 372, page 317. Best tool life, 68 feet of work travel, was obtained on the .063" thickness sheet at a cutting speed of 1000 feet/minute using a spray mist. When milling .125", .187" and .250" thickness sheet, tool life decreased considerably; maximum tool life was obtained at a cutting speed of 500 feet/min.

Figure 373, page 318, shows the effect of depth of cut and the effect of cutting fluid at different cutting speeds for the .125" thickness sheet material. Maximum tool life of 36 feet was obtained when taking a .025" depth of cut milling dry, at a cutting speed of 500 feet/minute. When using liquid CO_2, the tool life decreased slightly. However, a very significant decrease in tool life was observed when the depth of cut was increased to .050".

The effect of carbide grade is shown in Figure 374, page 318. The best carbide for high speed milling this alloy was a grade 883 (C-2). At a cutting speed of 1000 feet/minute and a feed of .010 in./tooth, a tool life of 30 feet of work travel was obtained. The next best grade was grade K-6 (C-2).

High Speed Edge Milling 6Al-4V Titanium Sheet (35-36 R_c)

Figure 375, page 319, shows the effect of cutting speed at constant feed when high speed milling 6Al-4V sheet .063" thick. Maximum tool life, 228 feet of work travel, was obtained at a cutting speed of 500 feet/minute and a feed of .010 in./tooth. Tool life decreased to 32 feet when the cutting speed was increased to 2000 feet/minute.

These data are plotted against feed rate at constant cutting speeds in Figure 376, page 319. Feeds in the range of .005 to .010 in./tooth provided the best tool life. Tool life decreased to about 20 feet of work travel when the feed was increased to .020 in./tooth for cutting speeds of 1000 feet/minute and higher.

The effect of cutting speed and sheet thickness is shown in Figure 377, page 320. Maximum tool life was obtained at a cutting speed of 500 feet/minute for the two thicknesses of sheet tested, .063" and .125". When the cutting speed was increased beyond 500 feet/minute, tool life decreased significantly for both sheet thicknesses. A tool life of 172 feet of work travel was obtained without liquid CO_2, compared with a tool life of 202 feet of work travel when using liquid CO_2. These data were obtained on the .125" thickness sheet at 500 feet/minute and a feed of .010 in./tooth.

Figure 378, page 320, shows the effect of feed for the .063" and .125" sheet thicknesses. A cutting speed of 1000 feet/minute was used with liquid CO_2 for these tests. A maximum tool life of 120 feet of work travel was obtained on the .063" thick material at a feed of .005 in./rev., while only 60 feet of work travel was obtained on the .125" thick material at this speed and feed. Tool life decreased when the feed was increased. At a feed of .020 in./tooth, tool life was very nearly the same for both sheet thicknesses, 30 feet of work travel.

The effect of depth of cut when varying the feed per tooth is shown in Figure 379, page 321. A tool life of 120 feet of work travel was obtained for a .050" depth of cut when milling at 1000 feet/minute using a feed of .005 in./tooth on the .063" thickness material. When the depth of cut was increased to .100", tool life decreased to 69 feet. However, for a .150" depth of cut, tool life was reduced only to 63 feet of work travel. When the feed was increased to .020 in./tooth, tool life decreased to values of 10 to 25 feet of work travel for the three depths of cut taken in these tests.

Figure 380, page 321, shows the effect of depth of cut when using liquid CO_2 and when milling this alloy dry. These tests were made at a cutting speed of 1000 feet/minute and a feed of .005 in./tooth. For a depth of cut of .050", a tool life of 120 feet was obtained using liquid CO_2. When milling dry with these conditions, tool life decreased to 102 feet. Tool life decreased to 70 feet of work travel when using liquid CO_2 and about 36 feet when milling dry for the .100" and .150" depths of cut.

High Speed Edge Milling 6Al-4V Titanium Sheet (35-36 Rc) (continued)

The effect of carbide grade, Figure 381, page 322, shows that the best carbide for high speed milling this alloy was grade 883 (C-2). This carbide provided a tool life of almost 40 feet of work travel at a cutting speed of 1500 feet/min. with a feed of .020 in./tooth. The next best two carbide grades were K-2S (C-6) and K-6 (C-2). A tool life of just over 30 feet of work travel was obtained with these grades.

High Speed Edge Milling HS-25 Alloy, 22-23 R_c

The high speed edge milling data obtained on HS-25 alloy are presented in Figures 382 through 385, pages 322 through 324.

The effects of cutting speed and feed are shown in Figures 382 and 383, pages 322 and 323, when milling this material dry. Best tool life, 90 feet of work travel, was obtained at 750 feet/minute. Tool life decreased rapidly when the cutting speed was reduced to 500 feet/minute or increased above 750 feet/minute.

Figure 382, page 322, shows the effects of cutting speed and depth of cut when high speed milling the HS-25 sheet material with liquid CO_2 and dry. For the two depths of cut tested, .025" and .050", better tool life was obtained when milling dry, compared with using liquid CO_2.

A feed of .0075 in./tooth produced maximum tool life when a cutting speed of 750 feet/minute was used, see Figure 383, page 323. At a cutting speed of 1000 feet/minute, the maximum tool life, 60 feet of work travel, was obtained at a feed of .015 in./tooth.

The effect of tool life on sheet thickness at different depths of cut is shown in Figure 384, page 323. Maximum tool life, 90 feet of work travel, was obtained on the .063" thickness sheet and a .025" depth of cut. Tool life decreased very rapidly when the depth was increased to .100". When high speed edge milling the .125" thickness sheet, tool life was considerably lower, 30 feet of work travel, at the depth of cut of .025". However, at the higher depth of cut of .100", there was very little difference in tool life between the .063" and .125" sheet thickness.

Figure 385, page 324, shows the different carbide grades tested in this program. The grade K-2S (C-6) was the best carbide tested. At a cutting speed of 1000 feet/minute and a feed of .010 in./tooth, this carbide grade provided a tool life of 40 feet of work travel when milling dry. The other grades tested provided tool lives between 15 and 25 feet of work travel.

High Speed Edge Milling PH 15-7 Mo Stainless Sheet (90 R_B)

The data obtained when high speed milling PH 15-7 Mo stainless sheet, annealed at 90 R_B, .063" thick, is presented in Figures 386 through 393, pages 324

High Speed Edge Milling PH [illegible] Mo Stainless Sheet (90 R_B) (continued)

[illegible] The effects of cutting speed at constant feed and feed rate at constant cutting speed are [illegible] 386 and 387, pages 32[illegible] and 325. These charts show that maximum tool life was obtained in the [illegible]000 to 2000 feet/minute cutting speed range and the .010 to .020 in./tooth feed range. The best tool life, 97 feet of work travel, was obtained using a cutting speed of 1500 feet/minute with a feed of .015 in./tooth. This data was obtained using liquid CO_2 as the cooling medium.

The data plotted in Figures [illegible] and 389, pages 325 and 326, show the effects of cutting speed and feed when high milling this material dry. It should be noted that tool life is increased about 50% over milling with liquid CO_2. A tool life of 150 feet of work travel was obtained at a cutting speed of 500 feet/minute and each of the feeds of .010, .015 and .020 in./tooth. When the feed was reduced below .010 in./tooth or increased above .020 in./tooth, tool life decreased significantly.

Figures 390 and 391, pages 326 and 327, show the effects of cutting speed and depth of cut on tool life when high speed edge trimming PH 15-7 Mo with liquid CO_2 and dry. A tool life of 150 feet of work travel was obtained for a .050" depth of cut when milling dry at 1500 feet/minute. Tool life decreased to 110 feet of work travel for a .100" depth of cut and 70 feet of work travel for a .150" depth of cut. Significantly, lower tool life values were obtained when using liquid CO_2.

The effect of type of cooling medium is presented in Figure 392, page 327. This chart shows that no increase in tool life was obtained when using liquid CO_2 or a soluble oil spray mist over cutting dry.

The effect of different carbide grades, Figure 393, page 328, shows that a grade K-2S (C-6) carbide was superior to the other grades tested. At a cutting speed of 2000 feet/minute and a feed of .010 in./tooth, the grade K-2S carbide provided a tool life of 67 feet of work travel. The second best carbide, grade K-6 (C-2), provided a tool life of 36 feet of work travel, while less than 25 feet of material was cut with grades 883 (C-2) and K-8 (C-3).

High Speed Edge Milling Rene 41 Sheet

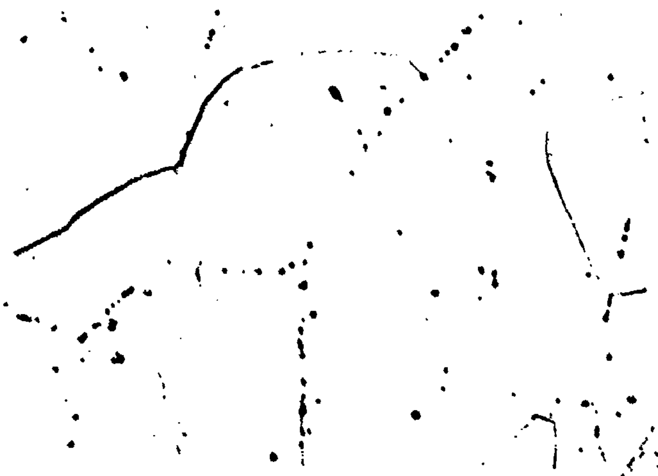
Cutting speeds ranging from 500 to 2000 feet/minute and feeds of .005 to .020 in./tooth were used with a variety of carbide grades in high speed edge milling of Rene 41 sheet material. The maximum tool life obtained under any of these conditions was only 4 feet of work travel; and, in addition, a large burr was left in the edge of the workpiece. Hence, the cut was not satisfactory.

An acceptable edge finish was obtained with a tool life of 2 feet of work travel at a cutting speed of 500 feet/minute and a feed of .005 in./tooth using liquid CO_2. The carbide was grade 883.

6Al-4V Titanium Alloy
Solution Treated and Rolled, 35 R_c

Microstructure consists of beta grains in an alpha titanium matrix.

Magnification: 500X **Etchant: Kroll's**



B-120VCA Titanium Alloy
Solution Treated, 35 R_c

Microstructure consists of equiaxed [illegible] of beta titanium plus strings of prior grain [illegible] carbides.

Magnification: 1000X **Etchant:** 1 part HNO_3
1 part HF
2 parts Glycerol

Figure 164

15-7 Mo, Mill Annealed, 90 R_B

Microstructure consists of equiaxed austenite grains with stringers of ferrite, elongated in the direction of rolling.

Magnification: 500X **Etchant: Kalling's**

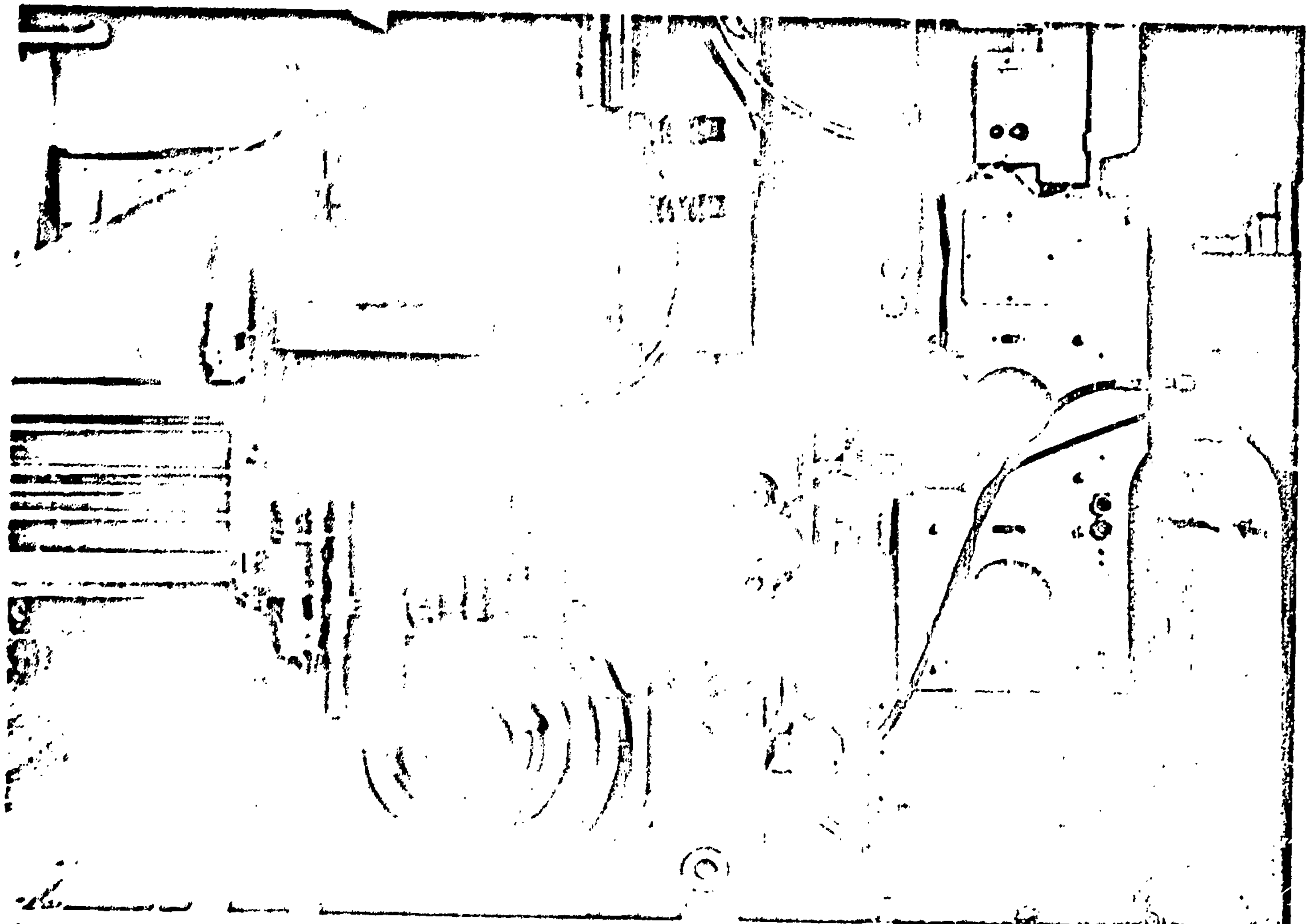
Haynes Stellite Alloy No. 25, Hot Rolled, 22 R_c

Microstructure consists of equiaxed "austenitic" grains plus random free carbides.

Magnification: 500X **Etchant: $HNO_3 + H_2O_2$**

Figure 365

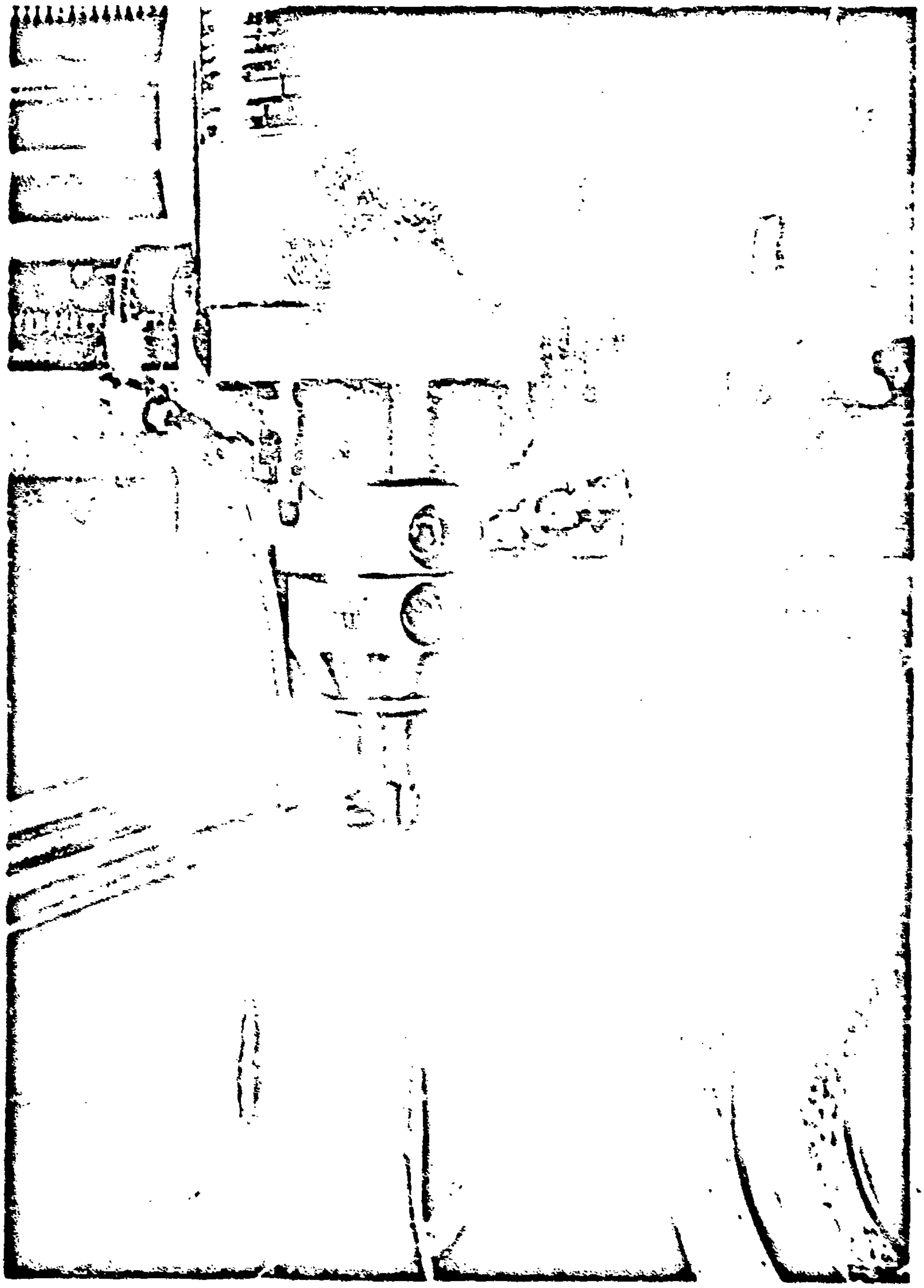
See Text, page 306



An overall view of 30" x 6' Gray planer and high speed milling head applied to this machine. The planer provides infinitely variable table speeds ranging from 40 inches/minute to 400 inches/minute. Spindle speeds ranging from 150 rpm to 9000 rpm are available on the milling head.

Figure 366

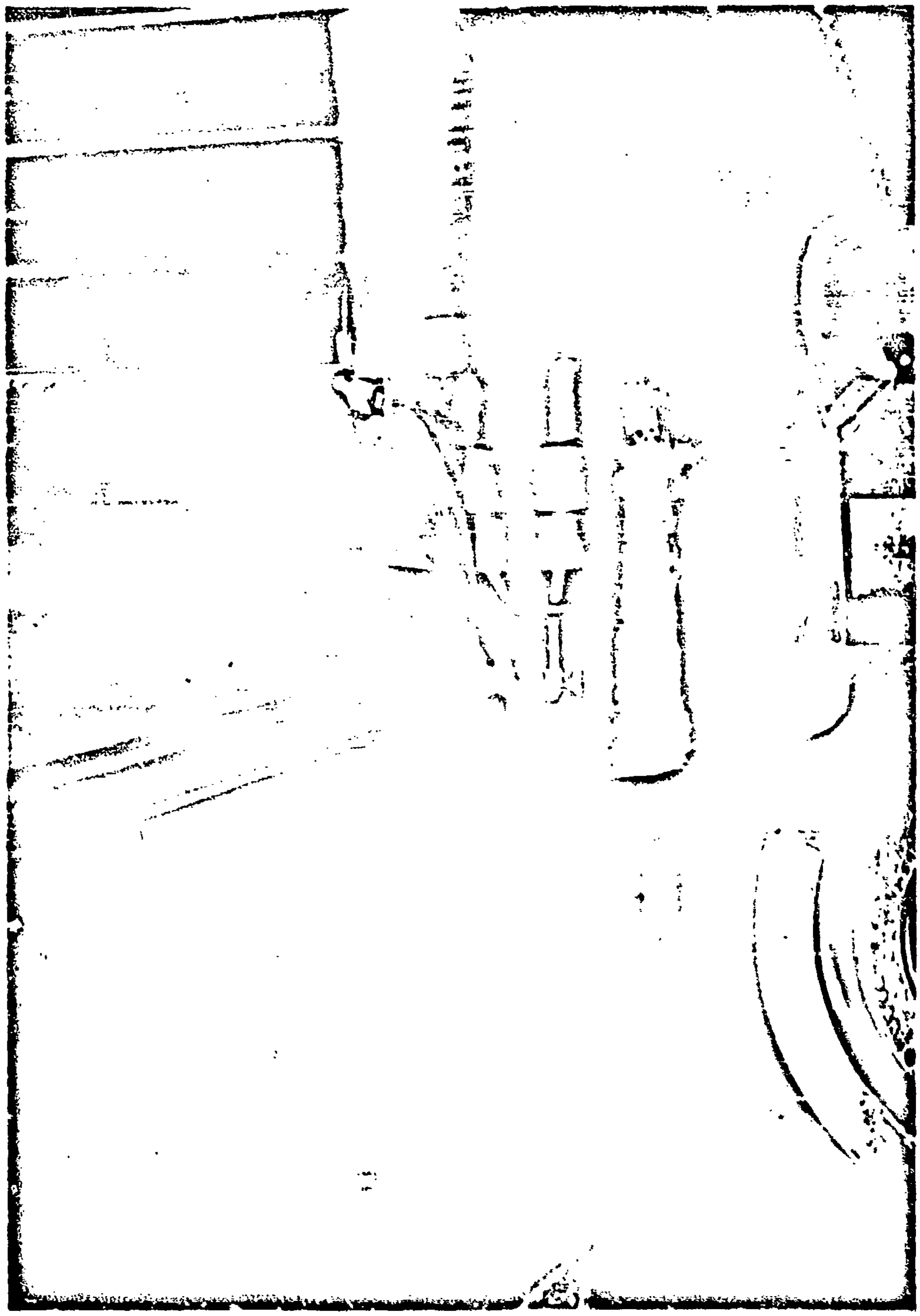
See Text, page 306



Close-up view of high speed milling cutter head and carbide throw-away type end mill. One of the two nozzles used to direct liquid CO_2 on the cutter and workpiece is shown.

Figure 367

See Text, page 306



Close-up of high speed edge trimming operation with liquid CO_2 spraying on workpiece and cutter. The cutter was revolving at 6000 rpm (2000 feet per minute) and the table was traveling at 270 inches/minute.

Figure 368

See Text, page 307

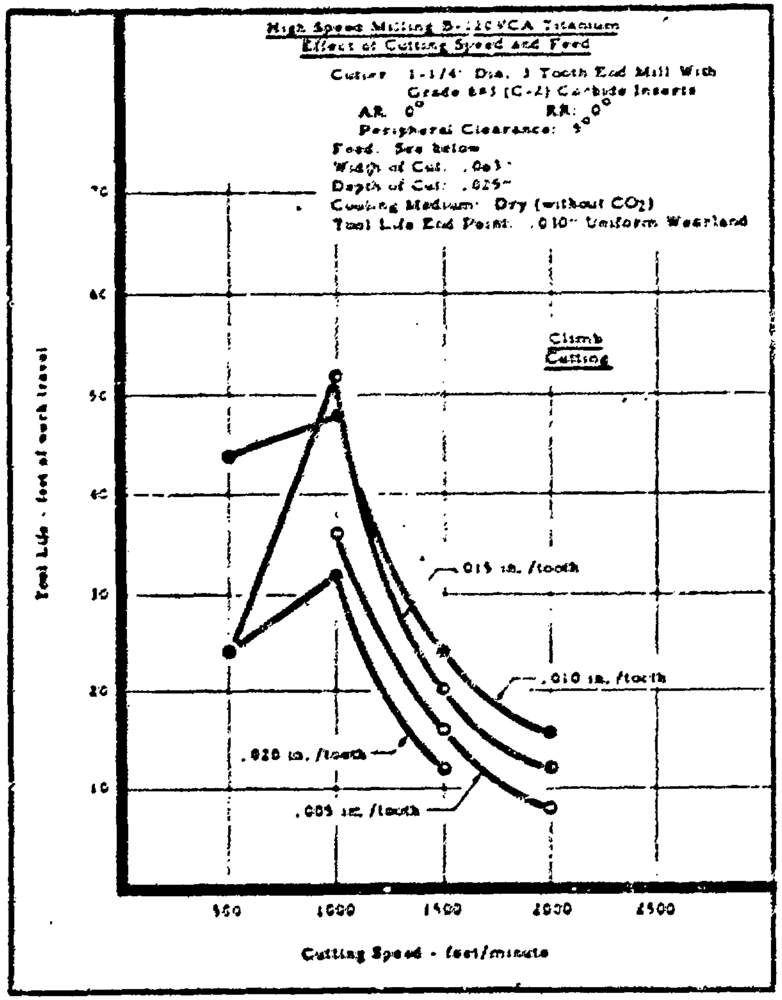


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Figure 369

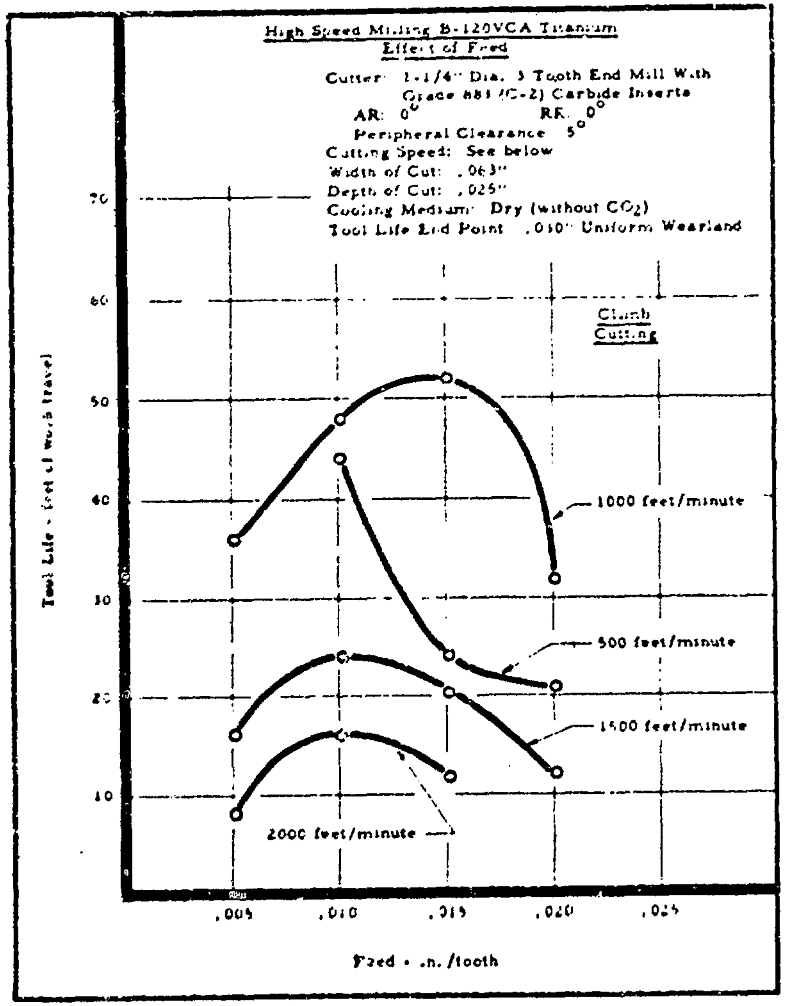

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Figure 370

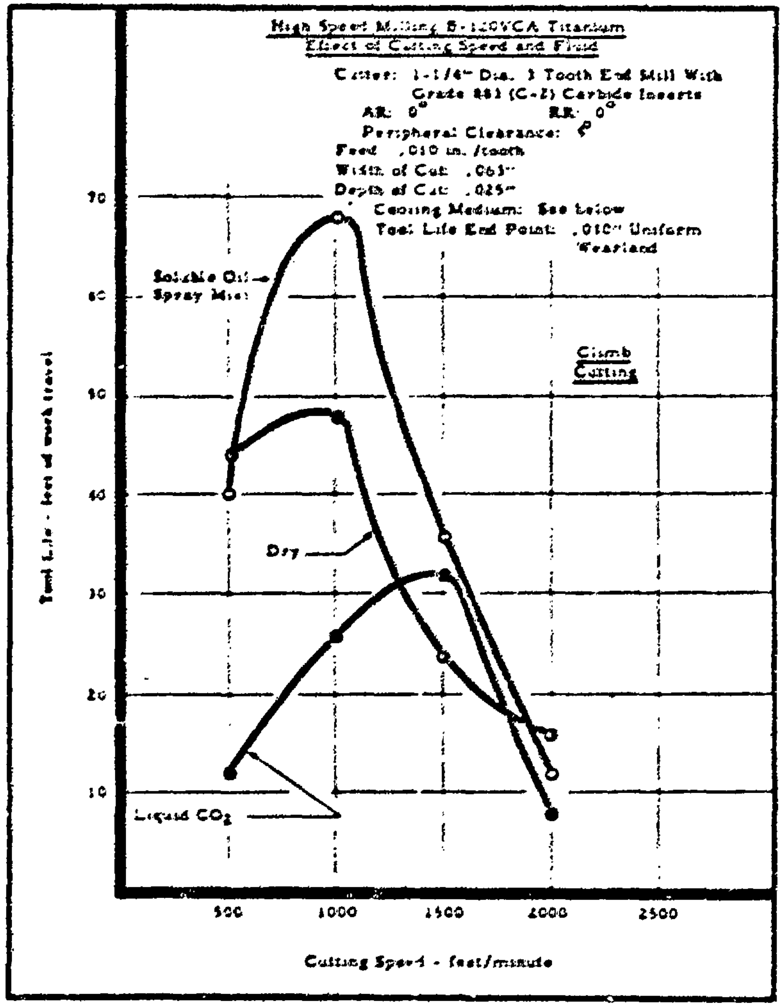

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Figure 171

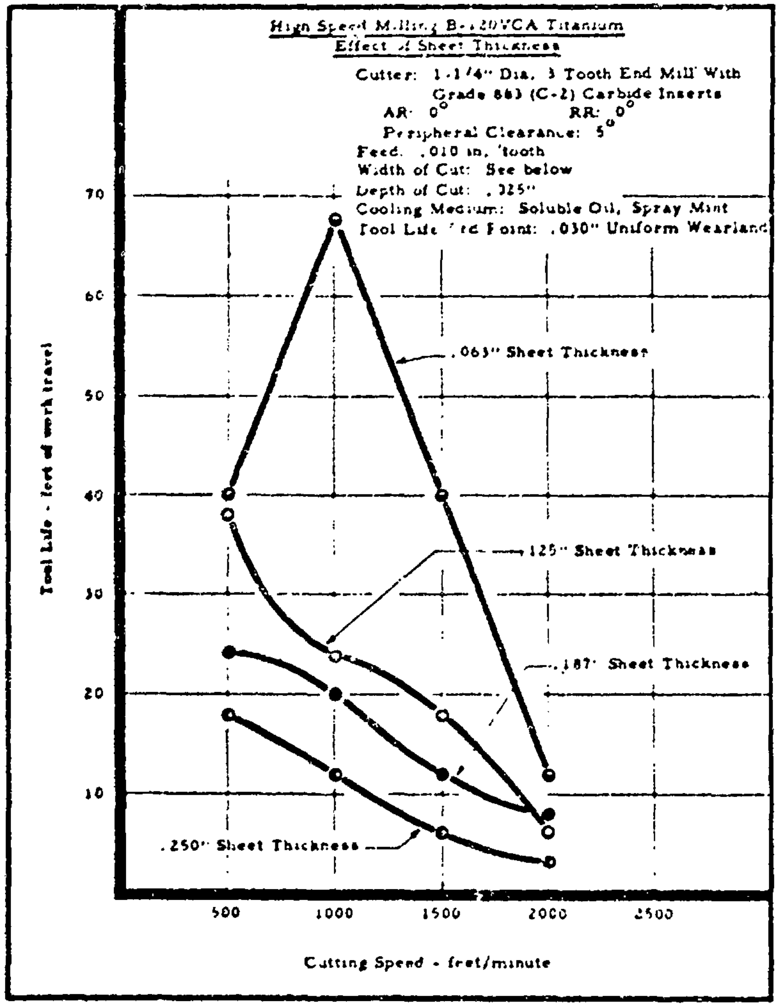

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Figure 172

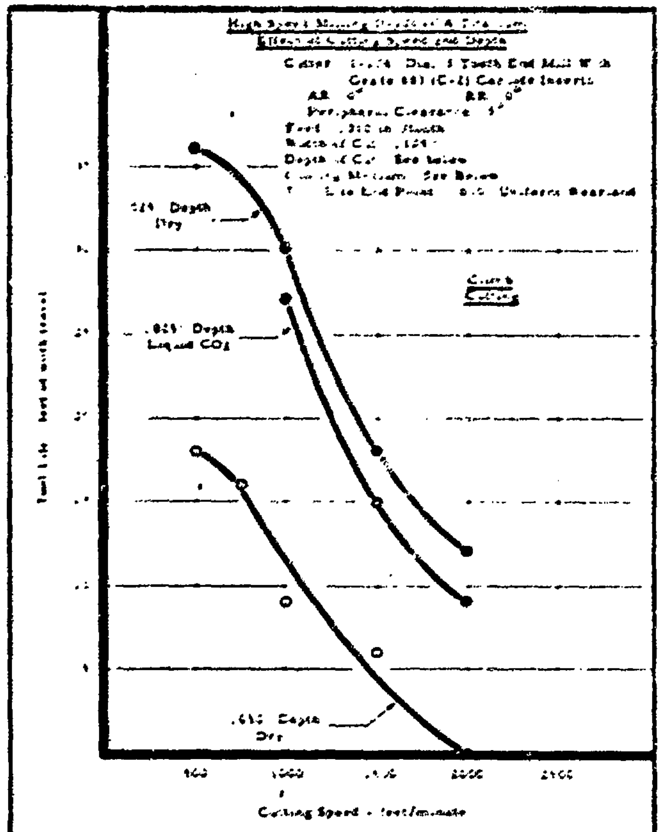

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Figure 373

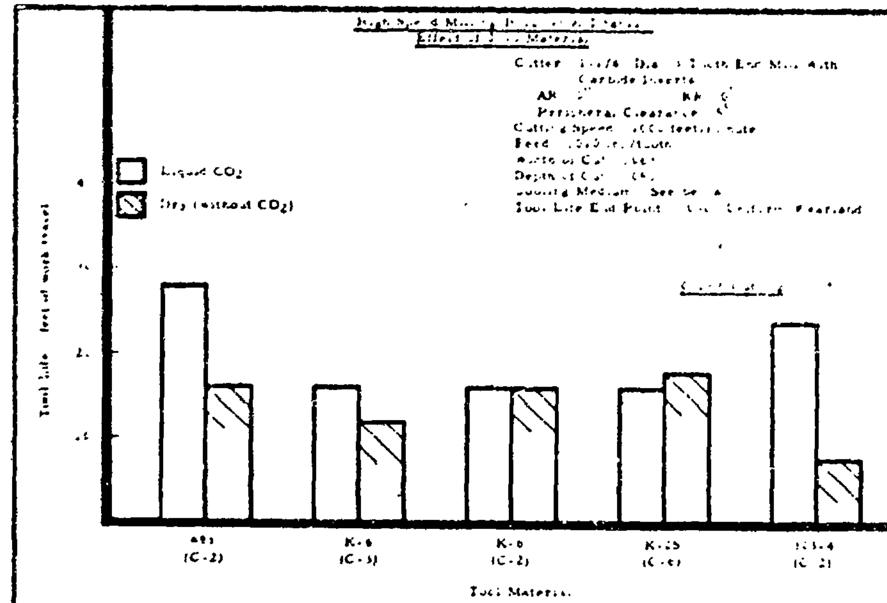

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Figure 374

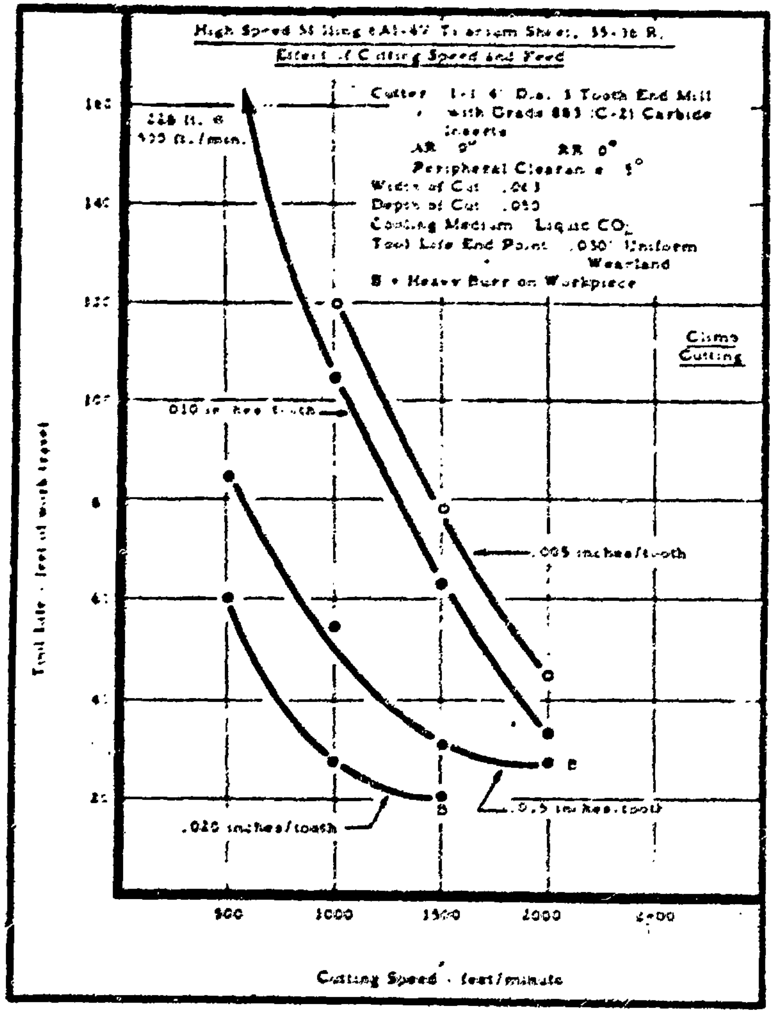

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Figure 375

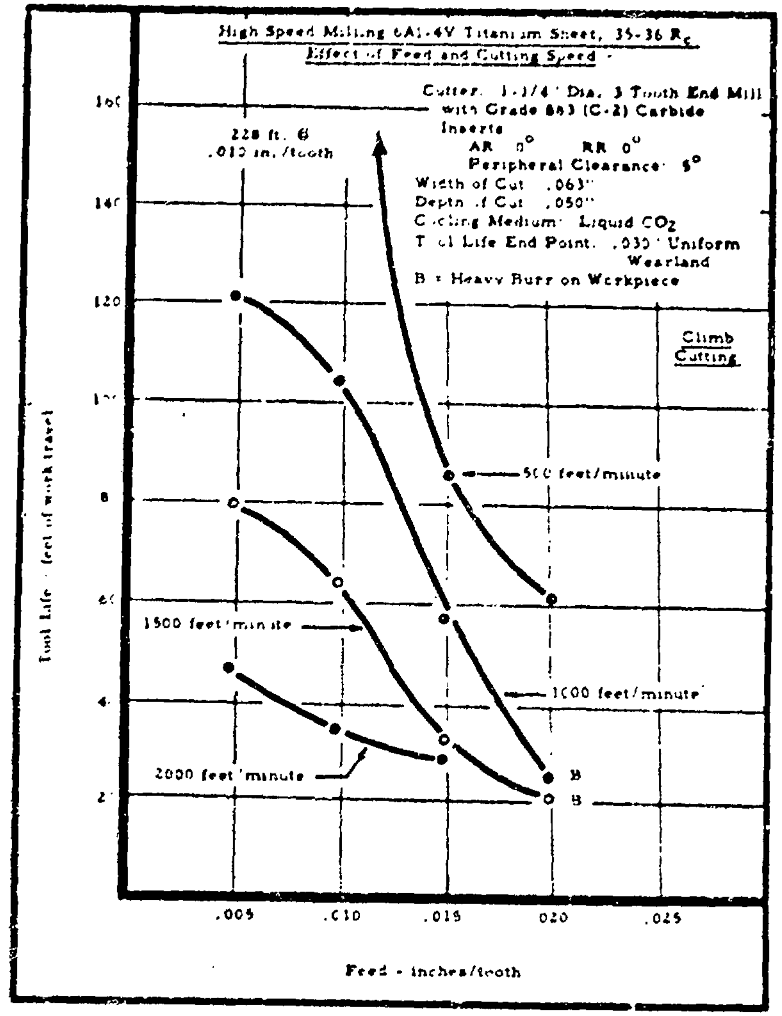

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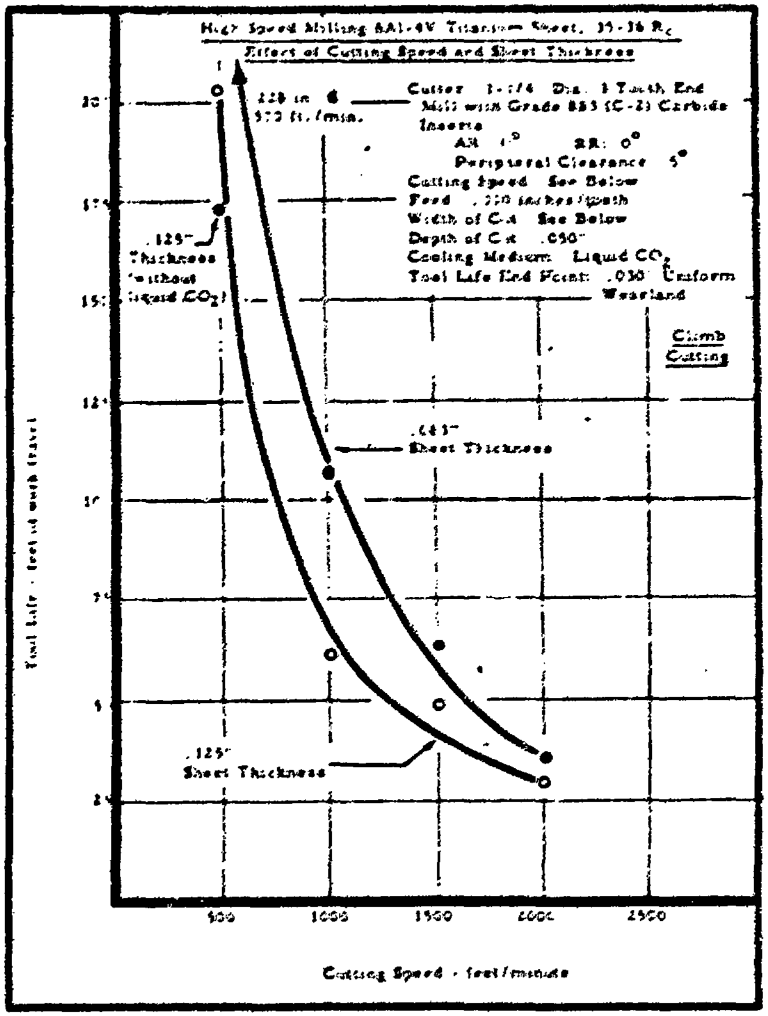
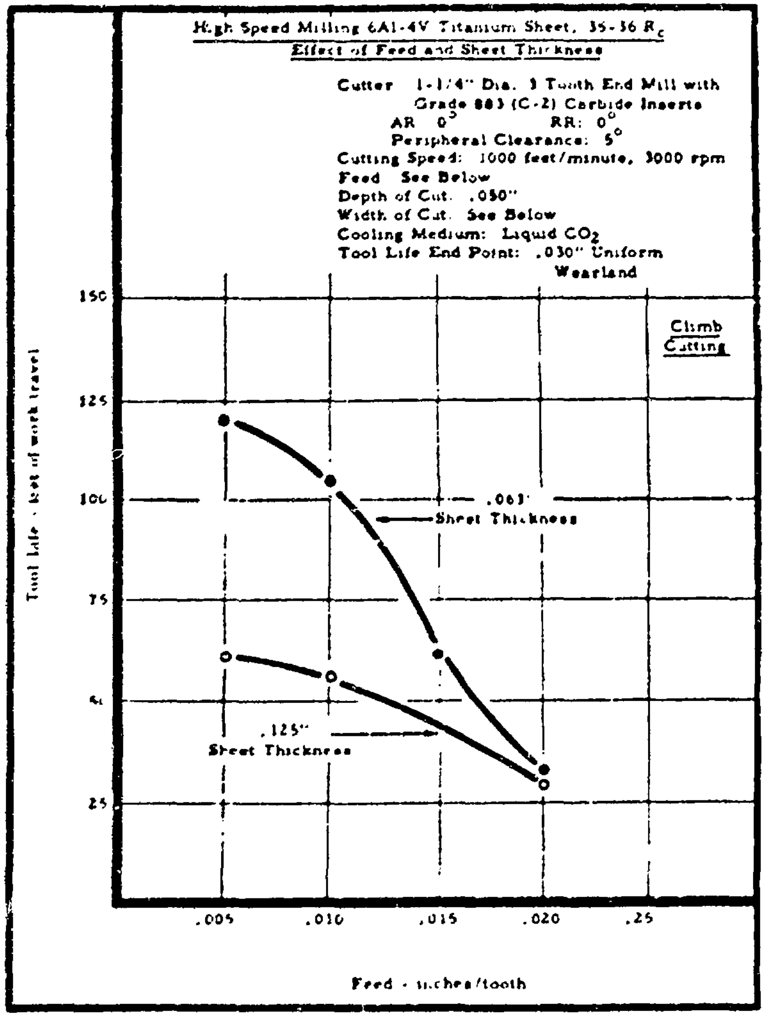
Figure 376



See Text page 308 Figure 377



See Text page 308 Figure 378

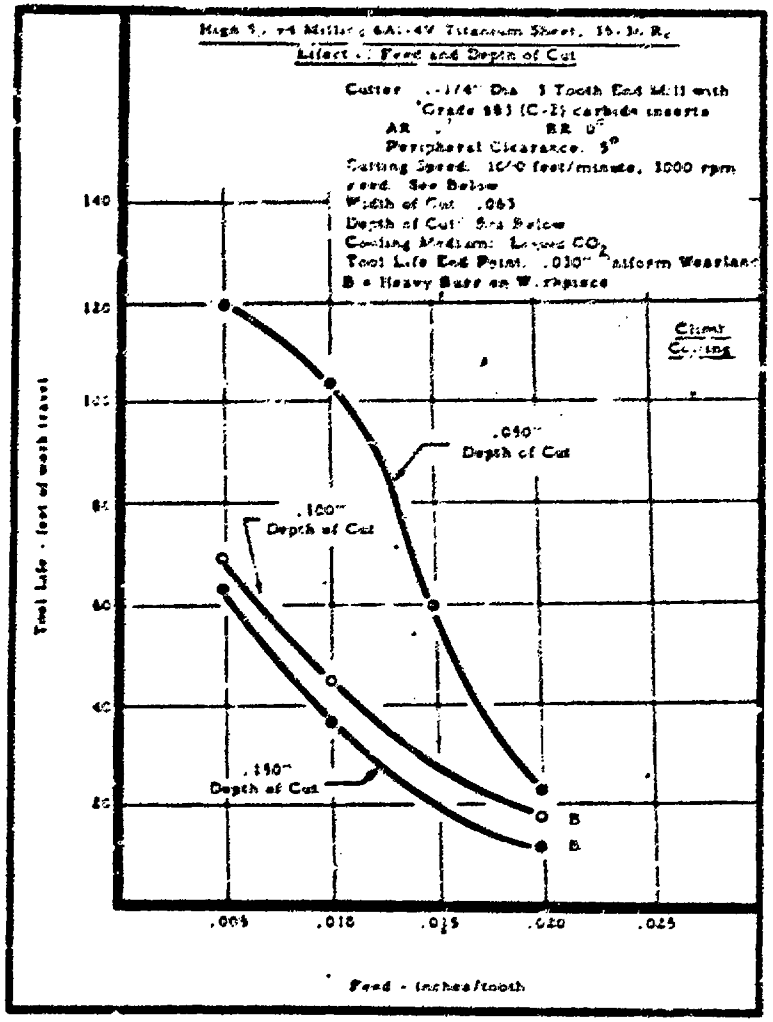


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Figure 379

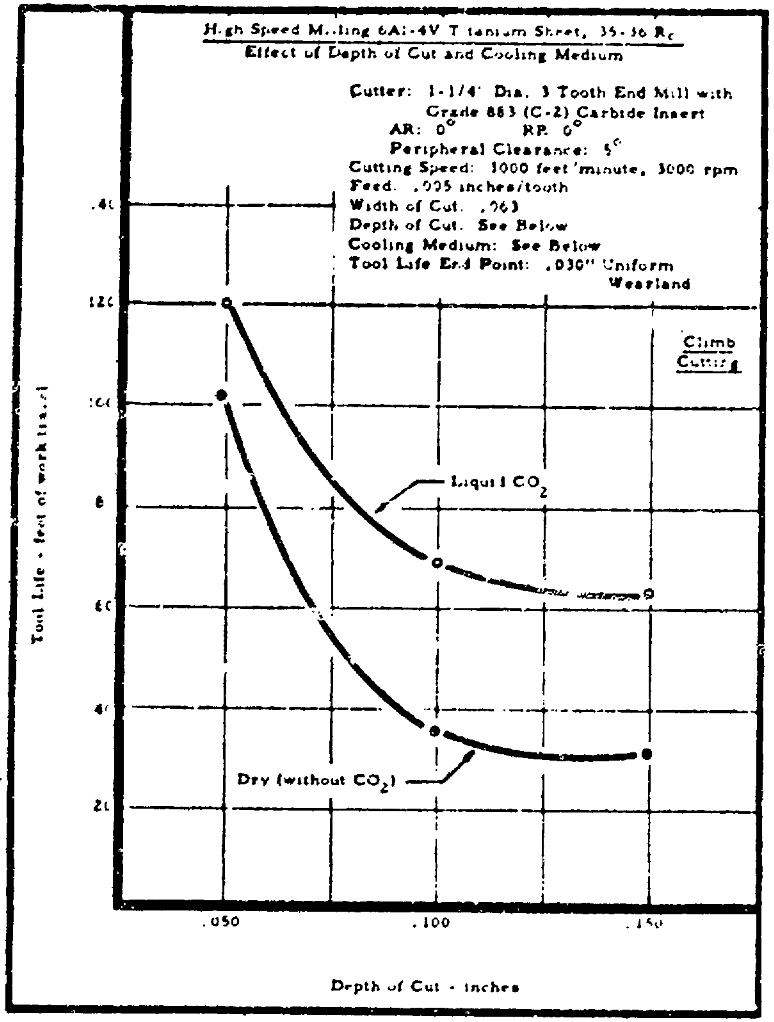

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Figure 380

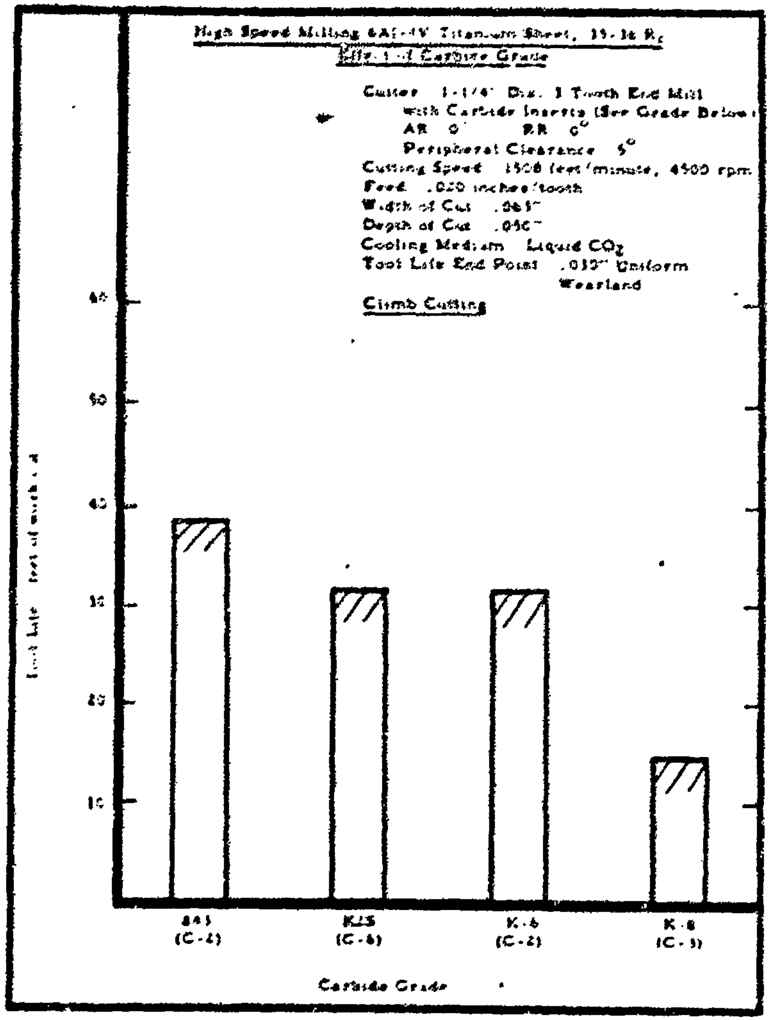

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Figure 361

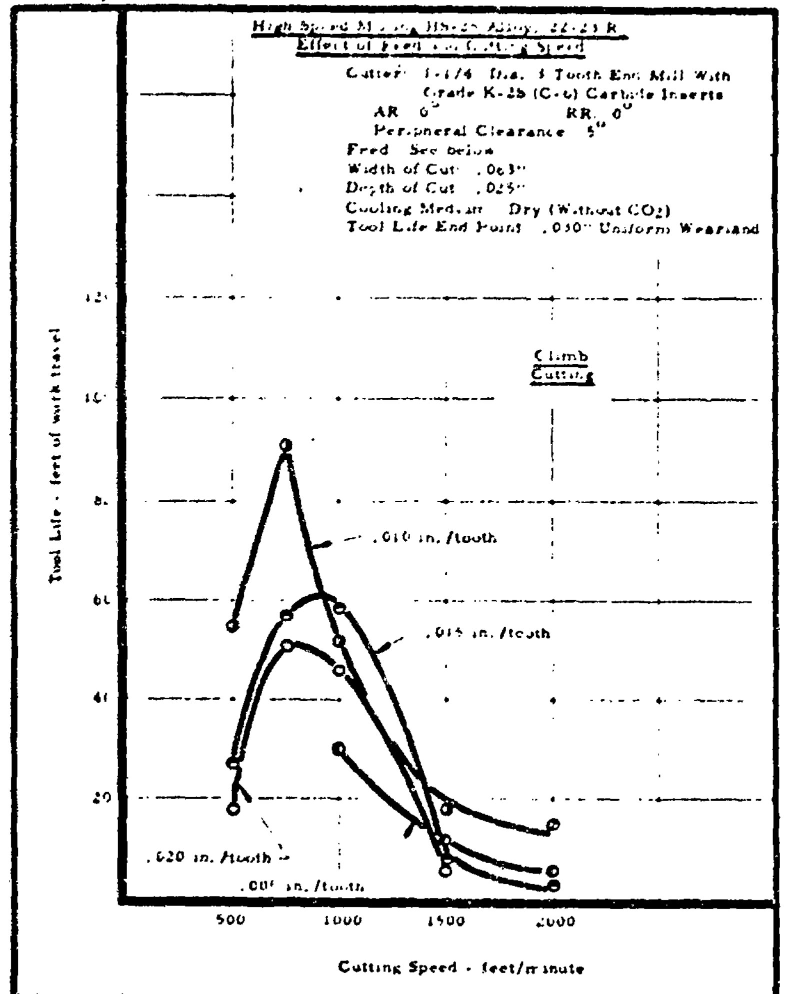

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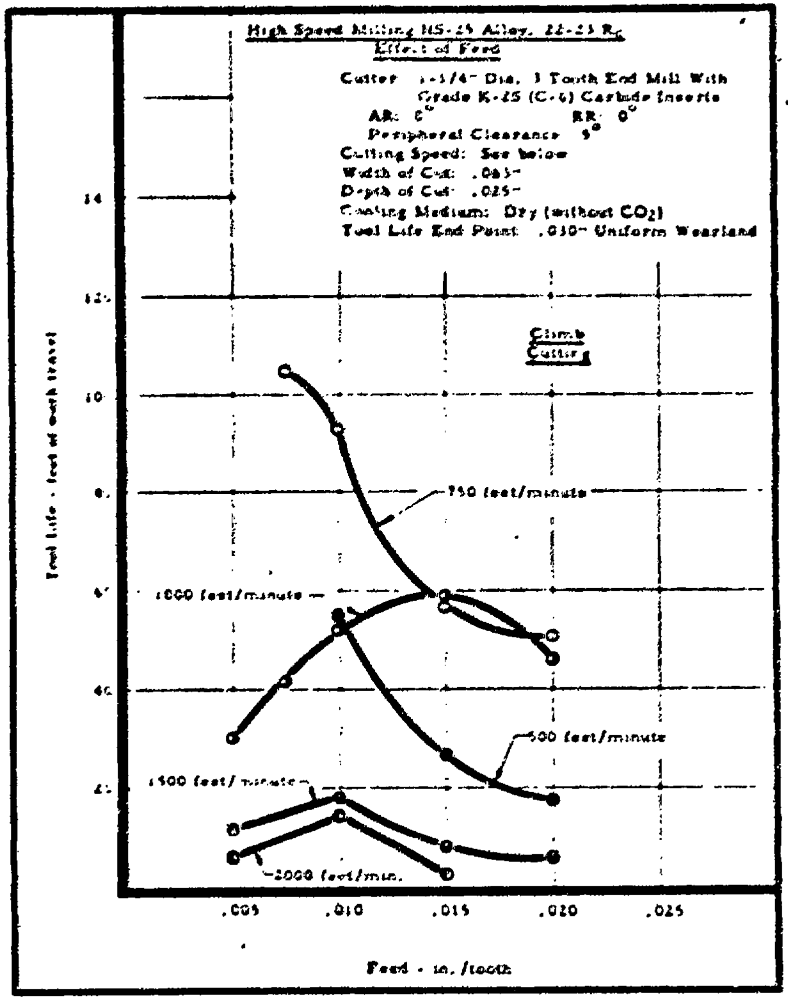
Figure 362



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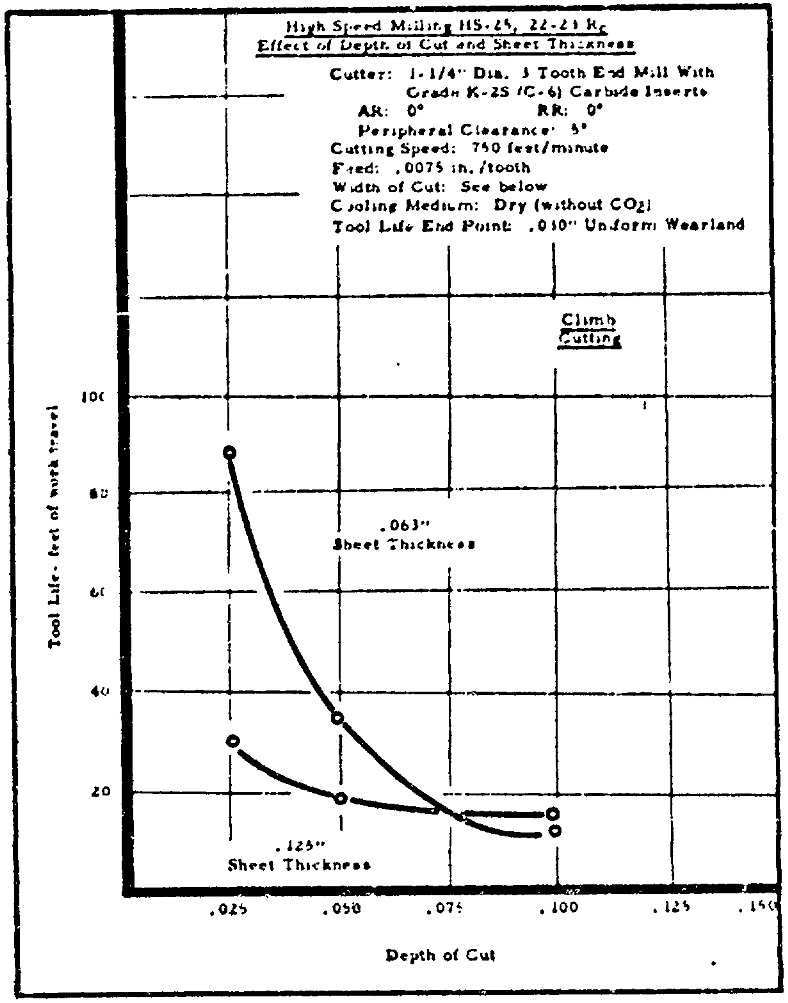

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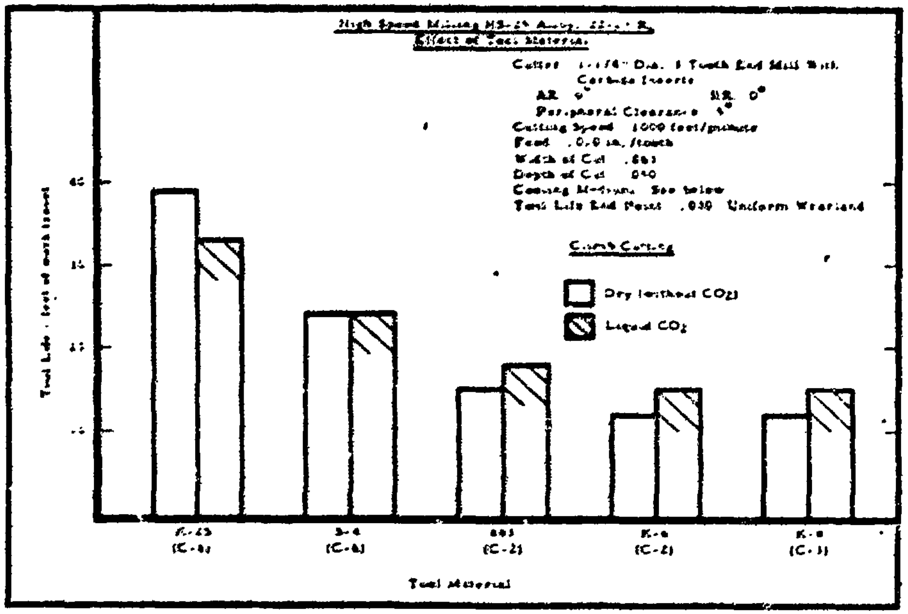

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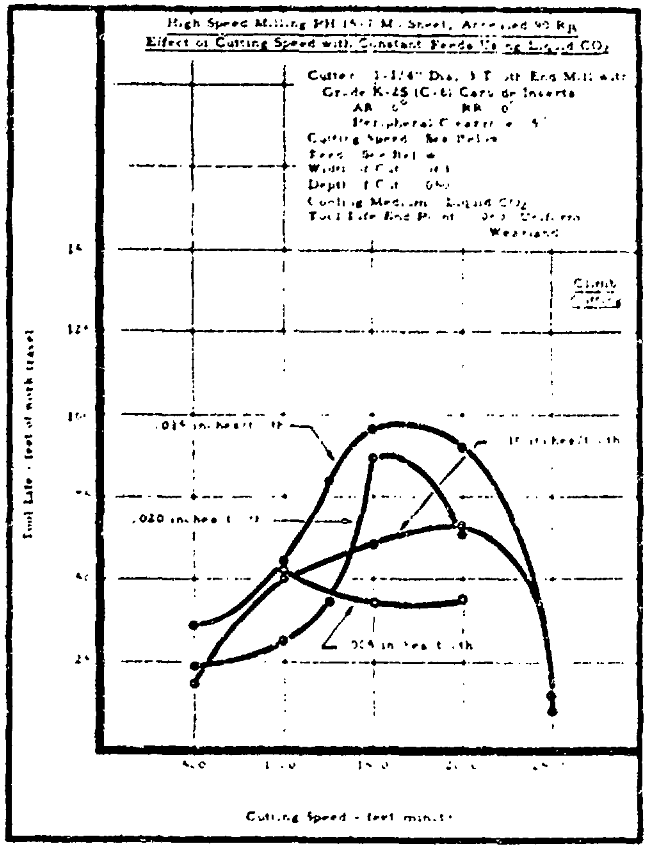

See Text page 510 Figure 386

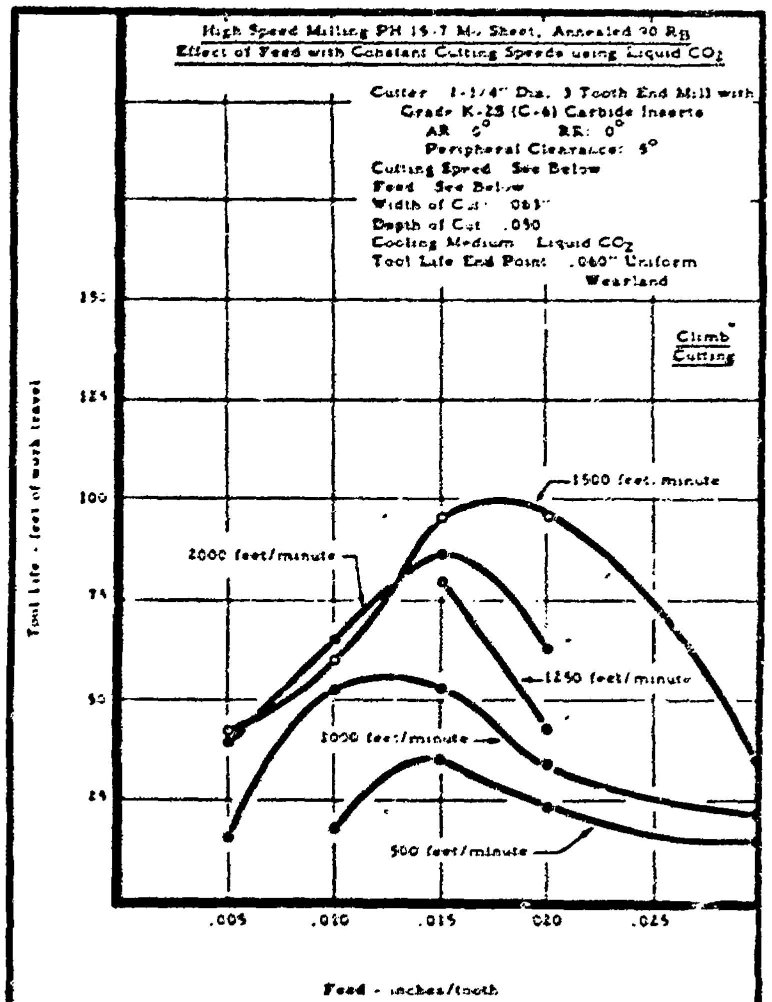

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Figure 387

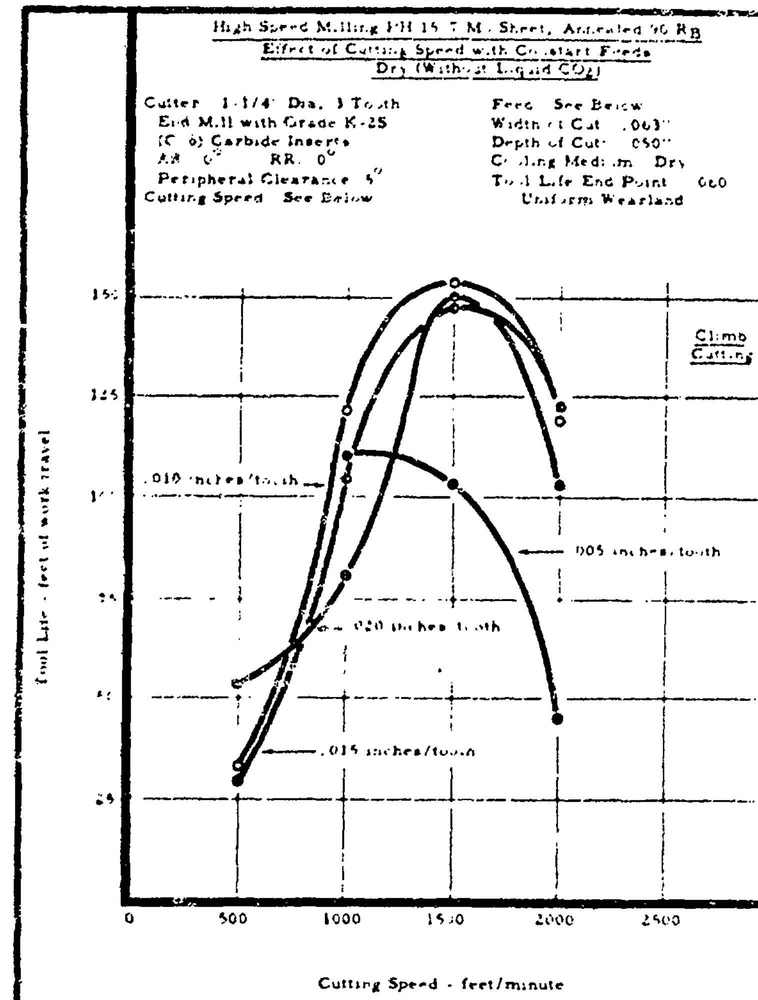

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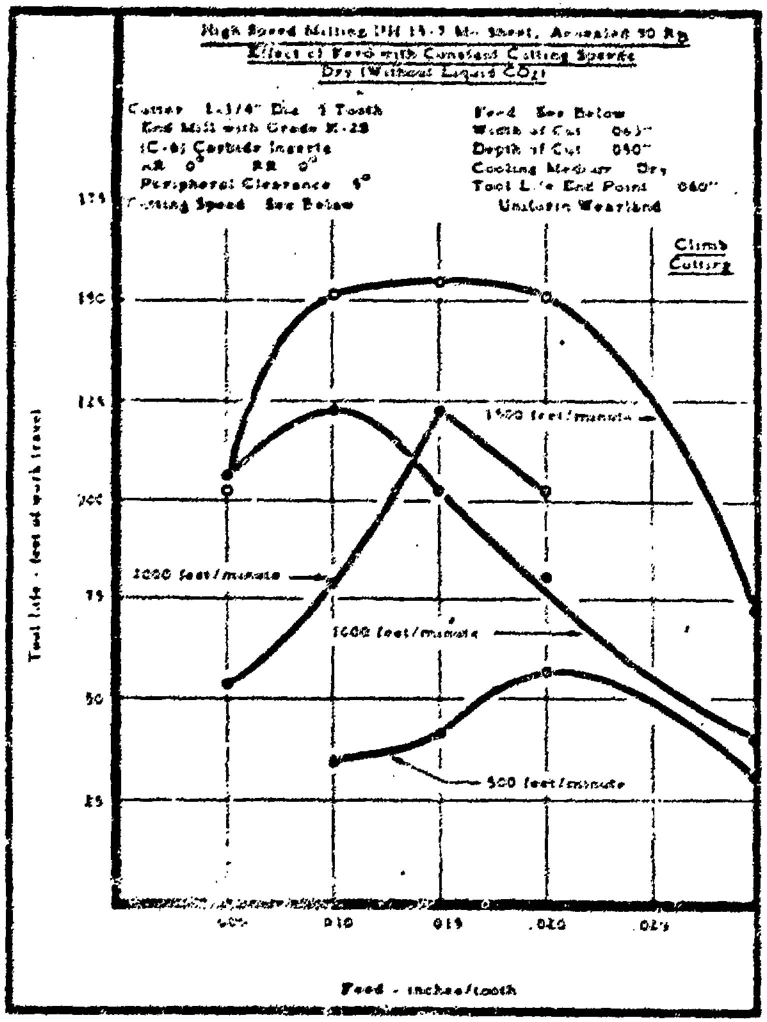
Figure 388



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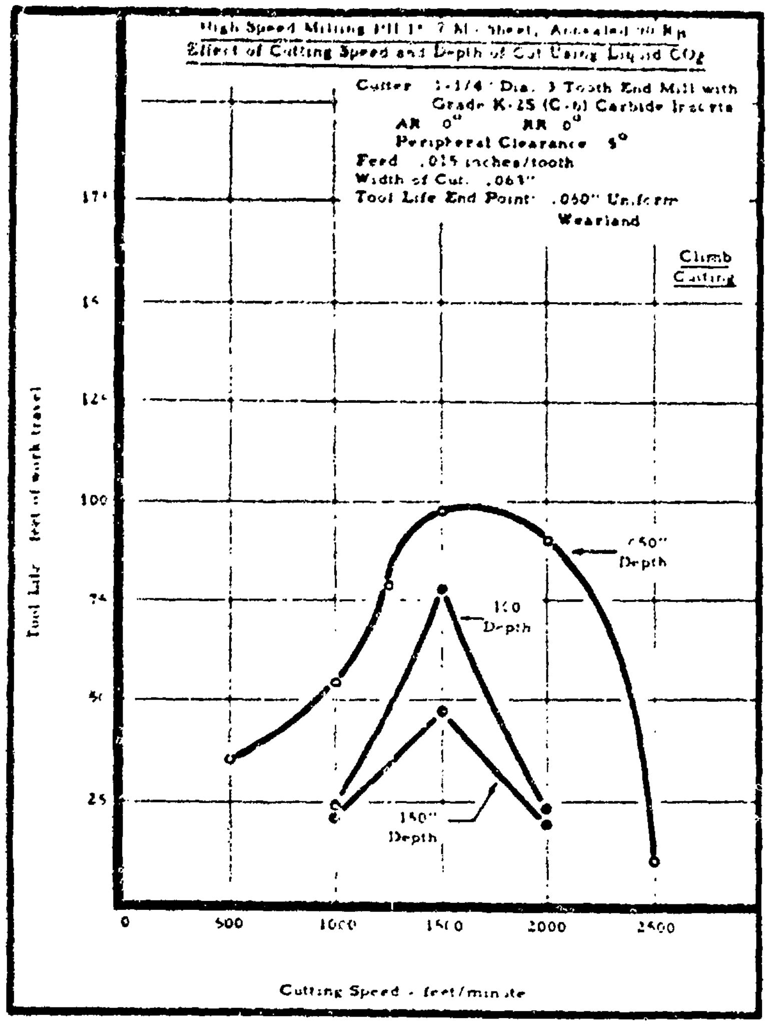

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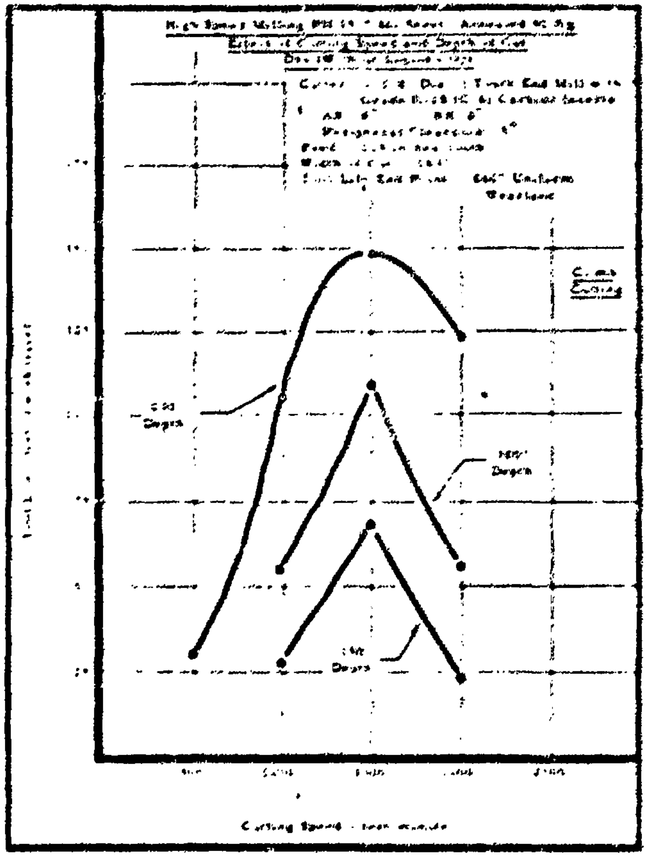

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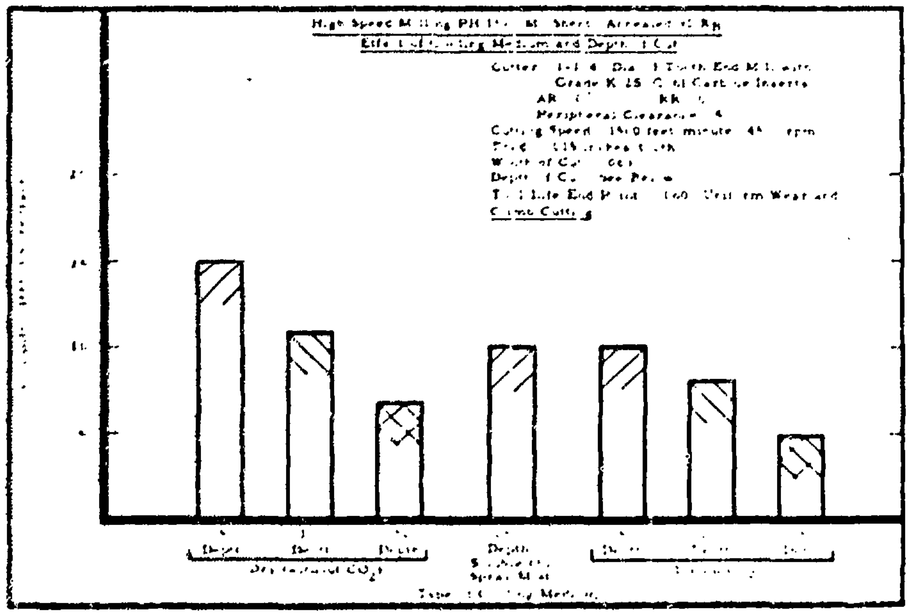

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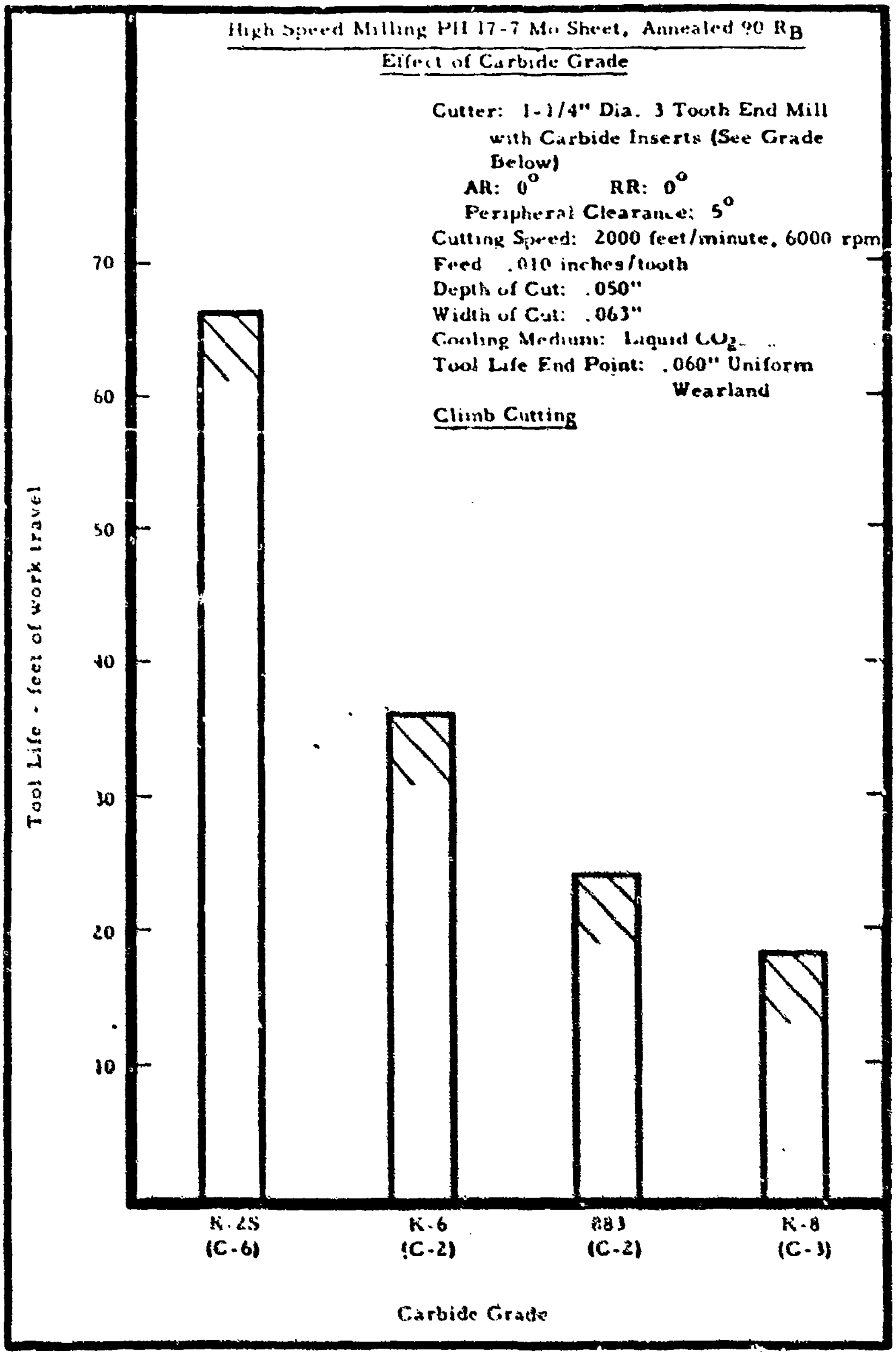

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Figure 393

XVI. APPENDIX

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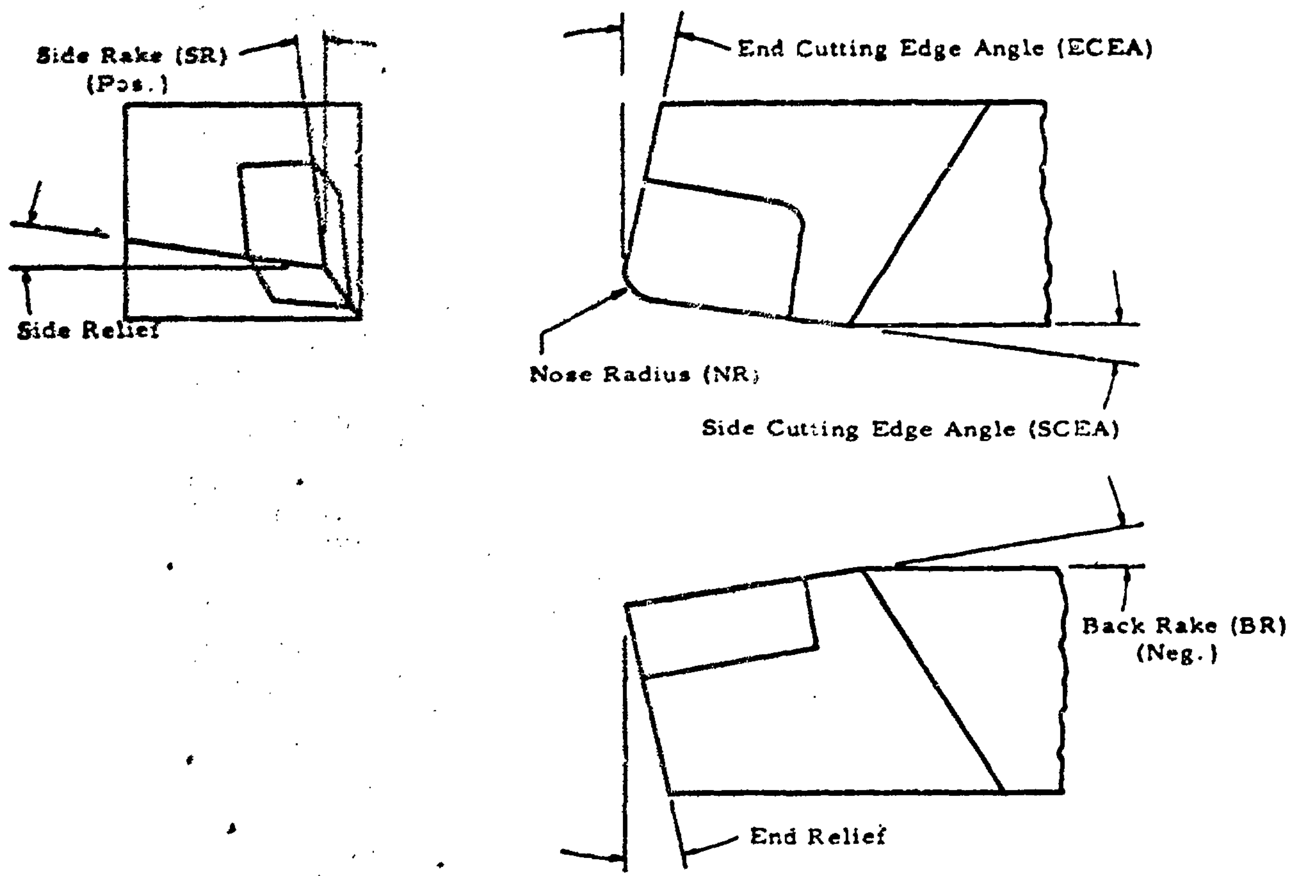
APPENDIX A

Lathe Tool Nomenclature



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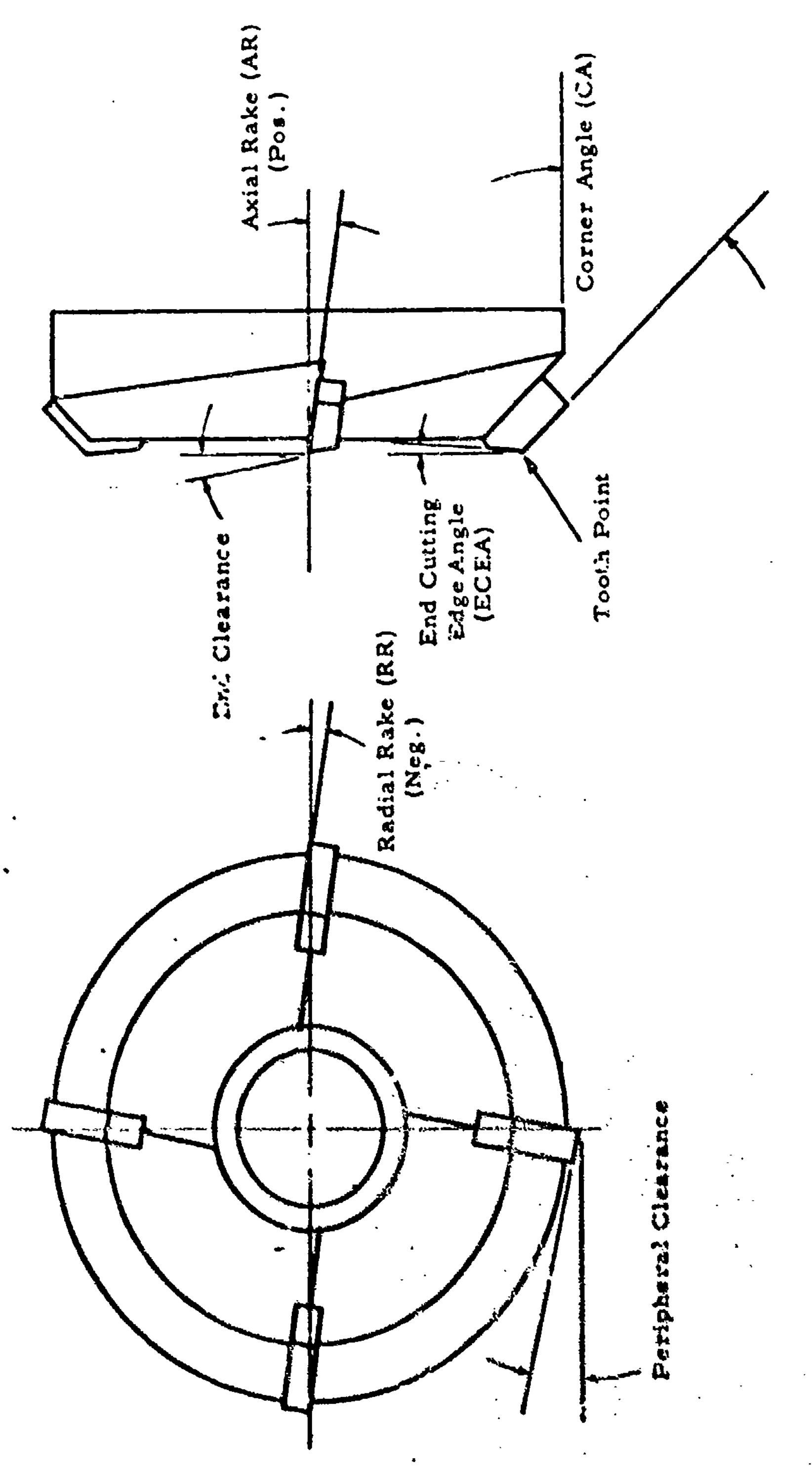
APPENDIX B

Face Mill Nomenclature



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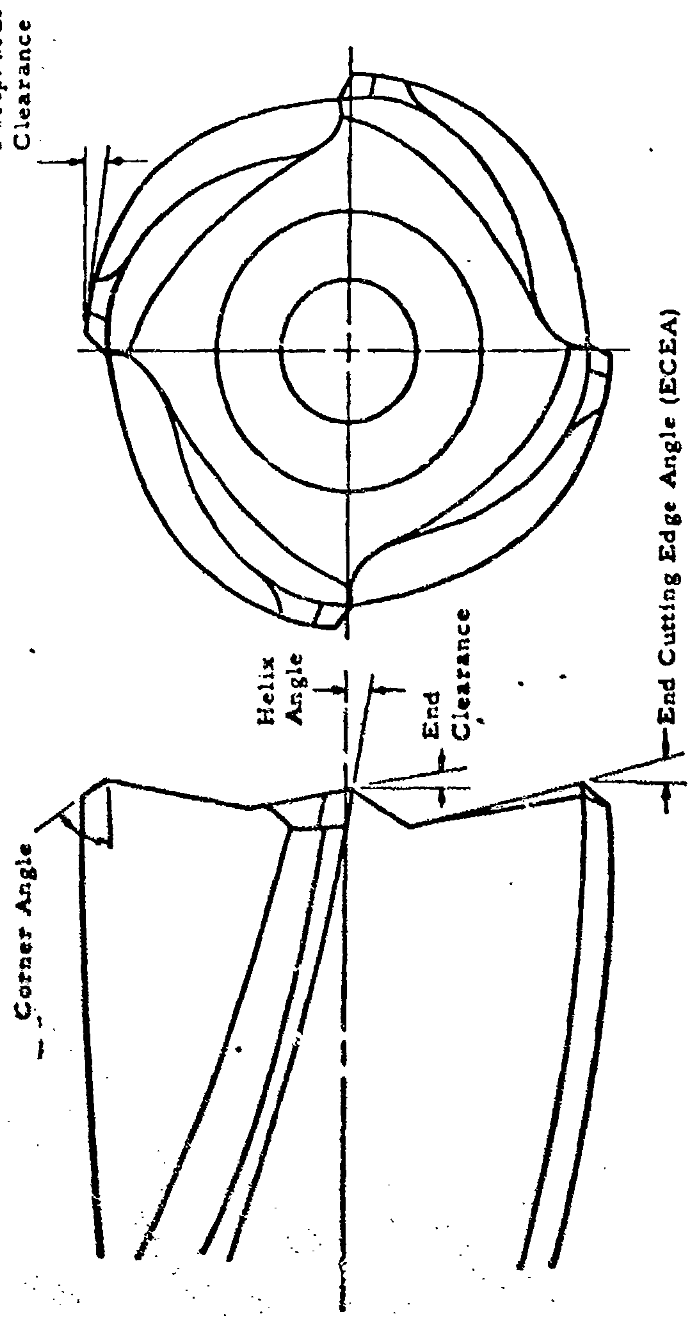
APPENDIX C

END MILL NOMENCLATURE



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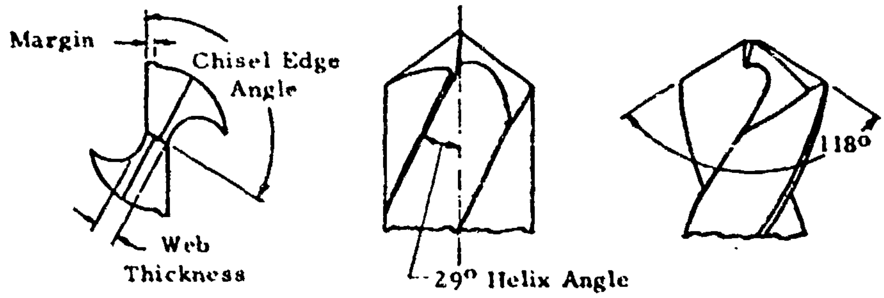
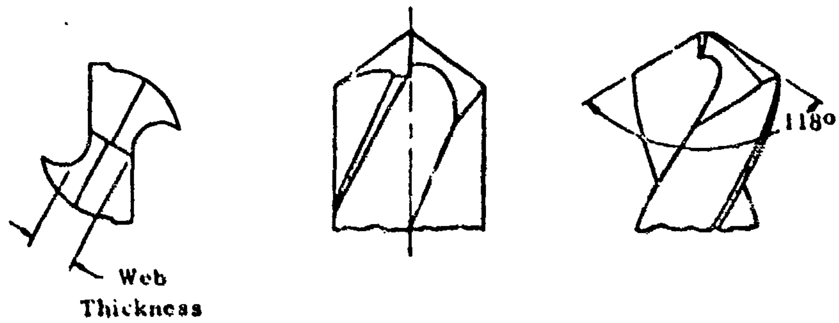
APPENDIX D

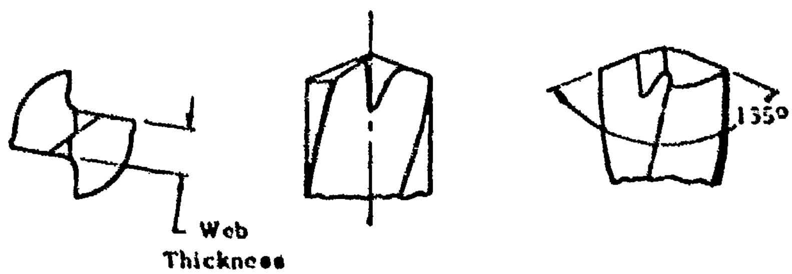
Drill Styles



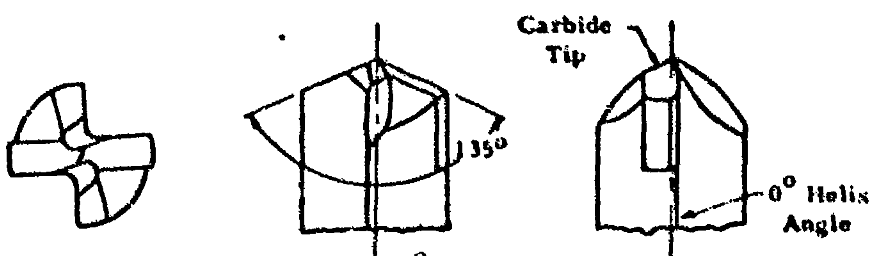
Standard Twist Drill - 29° Helix, Split Point



Heavy Web Drill - 29° Helix, Split Point



Heavy Web Drill - 12° Low Helix, Notched Point



Carbide Tipped Die Drill - 0° Helix, Notched Point

Mechanical Construction for Above Drills in Appendix G, Page 132

See Text, page 4

APPENDIX E

MECHANICAL CONSTRUCTION OF TEST DRILLS

Drill Style	Dia. (in.)	Length: Overall (in.)	Length: Flute (in.)	Helix Angle (degrees)	Web Thickness: At Point (% of dia.)	Web Thickness: Increase (in./in.)
Standard Twist Drill	.250	2-1/2	1-3/8	29	17	.025
Low Helix (12°) Heavy Web Drill	.250	2-1/2*	1	12	32	.026
Regular Helix (29°) Heavy Web Drill	.250	2-1/2*	1	29	40	.026
Carbide Tipped Die Drill	.250	4	2	0	36	.000
Regular Helix (29°) Solid Carbide Drill	.250	4	2-1/2	29	35	.000

* These drills were originally 4" long; the shank end was cut off to produce the stated length.

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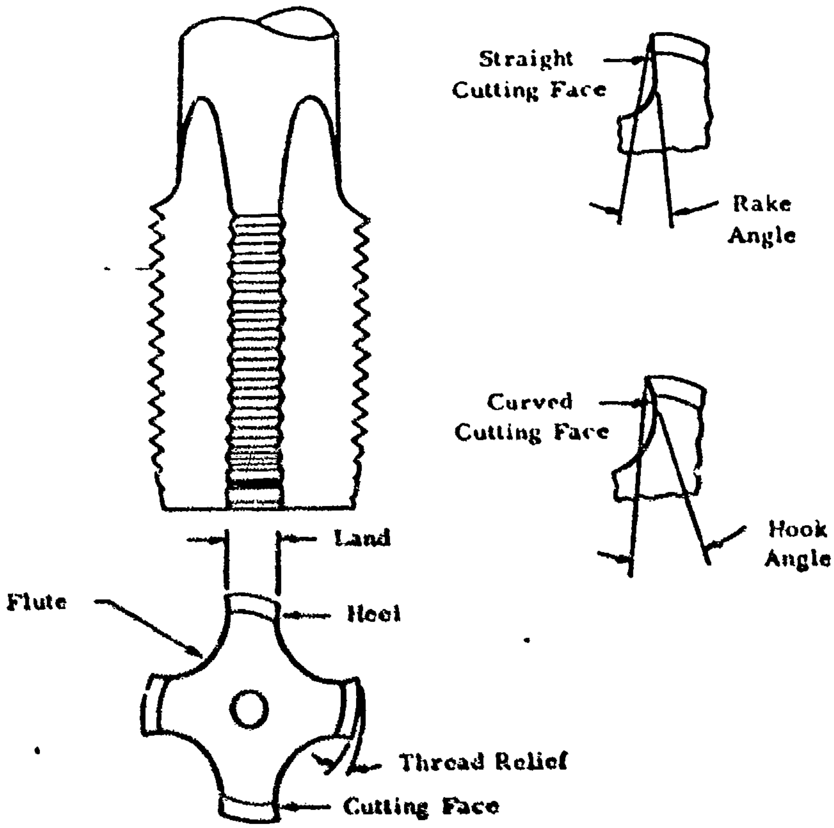
APPENDIX F

Tap Nomenclature



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APPENDIX G

CUTTING TOOL MATERIALS

High Speed Steel

Type	Nominal Composition
T-1	18% W, 4% Cr, 1% V
T-15	13% W, 4-1/4% Cr, 5% V, 5% Co
M-1	8% Mo, 4% Cr, 1% V, 1-1/2% W
M-2	5% Mo, 4% Cr, 2% V, 6% W
M-3	6% W, 4% Cr, 3% V, 6% Mo
M-7	1-3/4% W, 3-3/4% Cr, 2% V, 8-3/4% Mo
M-10	8% Mo, 4% Cr, 2% V
M-33	1-3/4% W, 3-3/4% Cr, 1% V, 9-3/4% Mo, 8-1/4% Co
Braecut	12% Co, 6-1/4% Mo, 5-1/4% W, 4-1/4% Cr, 2-1/4% V

Cast Alloy

	Nominal Composition
Tantung G	47% Co, 30% Cr, 15% W, 5% Others
Stellite 98 M2	41% Co, 32% Cr, 17% W, 10% Others
Crobalt No. 2	40% Co, 33% Cr, 18% W, 9% Others

Sintered Carbide

Grade	Application
C-1	Roughing Cuts - Severe: Cast iron, austenitic stainless, titanium, high temperature alloys, non-ferrous alloys
C-2	Roughing Cuts - Normal: Cast iron, austenitic stainless, titanium, high temperature alloys, non-ferrous alloys
C-3	Semi-Finish Cuts: Cast iron, austenitic stainless, titanium, high temperature alloys, non-ferrous alloys
C-3	Finishing Cuts: Cast iron, austenitic stainless, titanium, high temperature alloys, non-ferrous alloys
C-4	Precision Finishing: Cast iron, austenitic stainless, titanium, high temperature alloys, non-ferrous alloys
C-5	Roughing Cuts - Severe: Steels (alloy, martensitic, hot work die)
C-6	Roughing Cuts - Normal: Steels (alloy, martensitic, hot work die)
C-7	Semi-Finish Cuts: Steels (alloy, martensitic, hot work die)
C-7	Finish Cuts: Steels (alloy, martensitic, hot work die)
C-8	Precision Finishing: Steels (alloy, martensitic, hot work die)

See Text, page 5

APPENDIX H

Hardness Conversion Chart

Brinnel Hardness Number	Rc Hardness Number	R_B Hardness Number
372	40	---
363	39	---
352	38	---
332	36	---
313	34	---
297	32	---
283	30	---
270	28	---
250	24	---
240	22	100
230	20	98
223	--	97
212	--	96
207	--	95
197	--	93
179	--	89
170	--	87
163	--	85
156	--	83
149	--	81

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